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# Interpretability Analysis of Function Structures at Various Levels of Abstraction: A User Study

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INTREPRETABILITY ANALYSIS OF FUNCTION STRUCTURES AT  
VARIOUS LEVELS OF ABSTRACTION: A USER STUDY

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A Thesis  
Presented to  
the Graduate School of  
Clemson University

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In Partial Fulfillment  
of the Requirements for the Degree  
Master of Science  
Mechanical Engineering

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by  
Jonathan Edward Thomas  
May 2010

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Accepted by:  
Gregory M. Mocko, Committee Chair  
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Georges M. Fadel

## ABSTRACT

Function models are used during the conceptual design phase of the design process to model the intended use or objective of a product, independent of the products physical form. Function models also aid in guiding design activities such as generating concepts and allocating design team resources. Recent research efforts have focused on the formalization of functional models through a controlled vocabulary and archival of functional representations in computer-based repositories. However, the usefulness and interpretability of these function models has not been rigorously evaluated.

This thesis presents the results of two controlled user studies to ascertain the interpretability of functional representations at four levels of abstraction. These function models vary in abstraction in two dimensions: (1) the number of functions within the model and (2) the specificity of the terms used within the model. As a result of the two user studies, thirty four mechanical engineering graduating students were asked to identify consumer products based on their function model at various levels of abstraction. In addition to identifying the product, participants recorded time and any keywords/aspects in the functional model that aided them in their decision making. Analysis of the results indicates that interpretability of a function model increases substantially by using free language terms over a limited functional vocabulary. The results also indicate that interpretability increases by incorporating human interaction and environmental context of the product within the functional model. Lastly, the number of

functions within the functional model correlates with the identification of similar products.

## DEDICATION

This thesis is dedicated to my parents, family, and friends who have supported me throughout my collegiate career. This thesis is also dedicated to the loving memory of, Elder Dennis Joseph Ward

## ACKNOWLEDGMENTS

I must acknowledge my committee members; Dr. Gregory Mocko (Chair), Dr. Joshua Summers, and Dr. Georges Fadel for their support over the past two years. I especially want to give thanks to Dr. Mocko, who was always there to listen and provide advice on situations outside of research. I would also like to thank Clemson University's mechanical engineering staff; Ms. Tameka Boyce, Ms. Renee Gibson, and Ms. Gwen Dockins. Finally, I must acknowledge the members of the Clemson Engineering Design and Research (CEDAR) group for their support throughout my time here at Clemson University.

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## CHAPTER 1: FUNCTION-BASED DESIGN

The principal objective of this thesis is to investigate the interpretability of function structures at different levels of abstraction. This is accomplished through two user studies of first-year graduate students using four products at four levels of abstraction. Function structures are a function based, conceptual design tool and this chapter provides detailed background information on the ideology behind functional modeling.

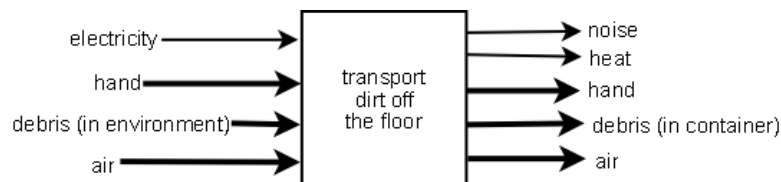
### 1.1 Functional Modeling

A function is the intended input/output relationship of a system whose purpose is to perform a task [1]. Ultimately, the functionality of a product justifies the products existence [2]. Functions are generally characterize by verb-noun statements, for instance, “increase torque” or “reduce pressure”. Modeling a product in terms of function has been identified as a well-accepted approach to the conceptual design phase of the design process [1-3]. Function models allow a design engineer to focus on “what” a product must do as opposed to “how” a product will complete a task. In addition, function models provide support for designers in that they aid in (1) generating product design concepts, (2) allocating design team resources, (3) product architecture, and (4) function models provide a basic systems approach to design, as needed for supporting experimental analysis methods [2]. There are several methods for modeling the functionality of a product such as functional lists, functional decomposition trees, and

function structures. Function structures are the modeling approach of interest for this thesis.

### 1.1.1 Function Structures

In mechanical design when sub-functions are combined into an overall function it produces what is known as a function structure[1]. Function structures are a robust and complete method for modeling a product’s functionality [2]. The first step in developing a function structure is to identify the input and output flows based on the needs of the customer; resulting in what is known as a black box model [4]. The black box abstractly expresses the overall need of the product and provides a technical relationship between the inputs and outputs of the system [2]. A black box model example for a vacuum cleaner is presented in Figure 1 [2]. The inputs and outputs of a function structure are categorized as either material, energy, or signal flows. Examples of material flows include gases, liquids, and solids. Energy flow examples include to mechanical, thermal, electrical, chemical, optical, and nuclear energy. Signal flows examples include magnitude, display, control impulse, or data.

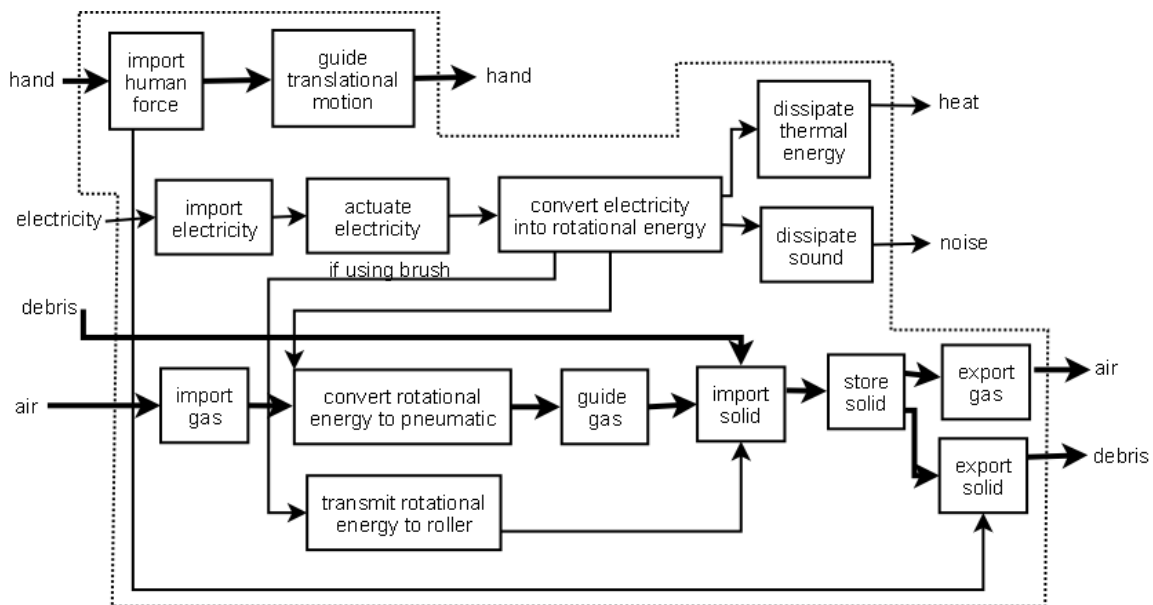


**Figure 1: Vacuum Cleaner Black Box Model [2]**

As shown in Figure 1, the overall need of the vacuum cleaner is to “transport dirt off the floor” and has four inputs and five outputs. The inputs are electricity, hand (human), debris, and air, and are categorized as energy, material, material, and material

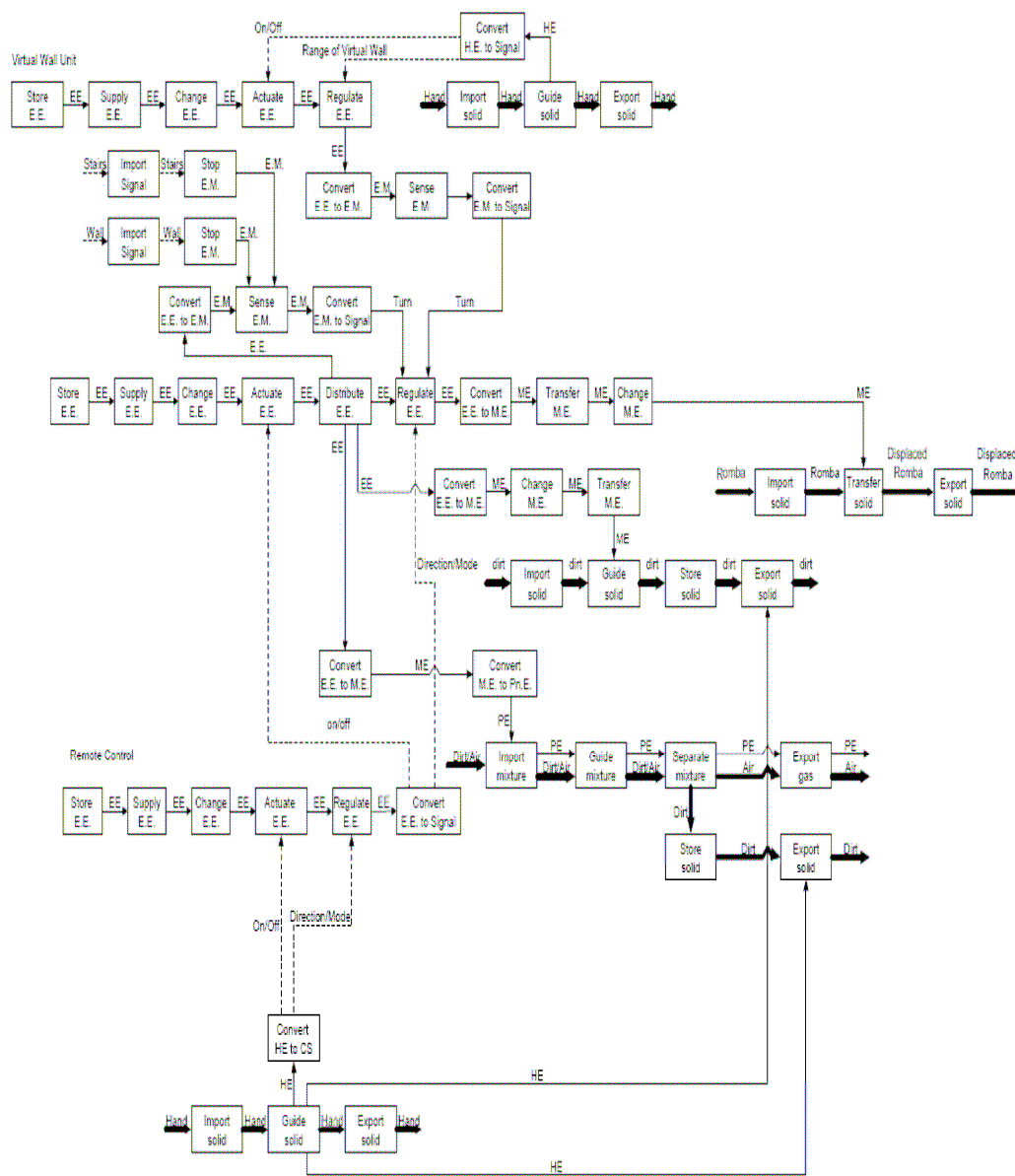


respectively. The outputs are hand (human), heat, noise, air, and debris; and are categorized as material, energy, energy, material, and material respectively. Figure 2 represents the functional decomposition of the vacuum cleaner in order to “transport dirt off the floor.” The function model, in has four Figure 2 still has four inputs and five outputs, but now consists of fifteen active verb-noun function flows. For instance, the functions “import human force”, “dissipate thermal energy”, and “actuate electricity” are active verb noun function flows within the function structure. From analyzing the various functions within the function structure, design engineers can begin to develop concepts on how to accomplish those functions. For instance, the “convert electricity into rotational energy” refers to the usage of a motor and with that information research can be done towards choosing an appropriate motor to complete the task of transmitting rotational energy to roller (if using brush) and converting that rotational energy to pneumatic energy.



**Figure 2: Vacuum Cleaner Function Structure [2]**

An additional function structure example for an iRobot Roomba is shown in Figure 3 [5]. An iRobot Roomba, which is pictured in Figure 4, is a self-directed robotic vacuum cleaner. Thus, like the vacuum cleaner from the previous example the overall need of the Roomba is to “transport dirt of the floor”. However, the Roomba function structure has ten inputs and seven outputs. The inputs include the storing of electrical energy (3), hand (2), stairs, wall, the Roomba, dirt, and dirt/air. The outputs are hand (2), displaced roomba, dirt, pneumatic energy (PE), air, and dirt. Compared to the vacuum cleaner, not only has the number of inputs and outputs increased for the Roomba, but the number of functions has increased as well. The Roomba has fifty-six functions; almost four times as many functions as the vacuum cleaner, even though both products have the same overall need. Therefore, the question must be raised, “Is the vacuum cleaner function structure complete or should Roomba’s function structure be reduced in size to eliminate ambiguity?” Here lies a potential discrepancy with function structures; the lack of complete formalization.



**Figure 3: iRobot Rumba Function Structure [5]**



**Figure 4: Picture of an iRobot Roomba[5]**

## 1.2 Functional Modeling Research Efforts

As illustrated in the vacuum cleaner and iRobot Roomba functions structure examples from the previous section, there is a lack of concrete formalization for function structures. Each of these products was designed to ‘transport dirt off the floor’ however the size and information contained respective function structure varies greatly. Thus, a challenge in the research area of function modeling appears to be the lack of a concrete formalism for how to construct, use, and manipulate function models. Research efforts have come from Stone and colleagues, with the development of the Functional Basis and the design repository to aid in the formalization of functional modeling [6]. The Functional Basis is a standardized set of function related terms to allow design engineers to describe the functionality of a product in a consist manner [7]. The design repository is web based, and contains functional information for over 130 reversed engineered and disassembled consumer based products [8]. In addition, researchers from Clemson University have developed nine function pruning rules, based on a product’s composition to aid in the formalization of functional decomposition [9]. The Functional Basis, design repository, and composition rules efforts are discussed in further detail in Section 3.1,

Section 3.2, and Section 3.3 respectively. However, the contribution of this thesis is to present the findings of an experimental user study developed to investigate the interpretability of function structures. The contribution of this research is discussed in further detail in Chapter 2:.

### 1.3 Thesis Outline

The results and analysis of two user studies conducted to investigate the interpretability of function structures are presented in this thesis. This thesis is organized into eight chapters. Function based design was discussed in Chapter 1:. Chapter 2:, outlines research gaps and opportunities within functional modeling as well as presents research questions and the associated research task. In Chapter 3: a frame of reference is presented, providing information on recent research efforts in functional modeling. In Chapter 4:, the levels of abstraction used to answer the research questions from Chapter 2: are discussed. In Chapter 5: and Chapter 6: an overview of each user study is presented. In Chapter 7: a comparison between the two user studies is presented. In Chapter 8: conclusions are drawn, research questions are answered, and future work is identified.

## CHAPTER 2: RESEARCH GOALS

### 2.1 Research Gaps

Design engineers use various methods of functional modeling to describe “what” a product must do as opposed to “how” a product must complete a task during the conceptual design phase [2]. However, functional modeling has yet to be fully formalized. The lack of functional modeling formalization is illustrated in Figure 2 and Figure 3, which are the function structures for a vacuum cleaner and an iRobot Roomba. Both of these products were designed to transport dirt of the floor; however the functional decomposition approach is different for both of these products. The authors of the Roomba function structure felt that certain contextual information needed to be included in the functional description of the Roomba, while the creator of the vacuum cleaner felt that some contextual information was not necessary. In practice functional modeling formalization is important for repeatable and meaningful results [7]. Research has been done to assist in the formalization effort of functional modeling; such as the development of a functional basis [7], a design repository [5], and pruning rules for function structures [9]. However, the usefulness and overall interpretability of these efforts have not been rigorously studied in the literature. This is fundamentally the research gap that is addressed in the research presented in this thesis.

In this research function structure interpretability is defined on two levels. The first level is the ability to identify the exact product for which the function structure was originally created. The second level is represented by the ability to identify products that

accomplish a similar high level purpose, though not the exact product. It is asserted that interpretability is related to how function models can be used in conceptual design [1]. Further; interpretability, as defined in this research, can be measured and related to consistency and understandability of function models.

## 2.2 Research Questions

To address this interpretability gap, user studies were completed to ascertain the interpretability of functional representations at various levels of abstraction. The function models vary in abstraction in two dimensions: (1) the number of functions within the model and (2) the specificity of the terms used within the functional models. Here, specificity is the dimension related to the choice of words used within the models, ranging from free natural language to the controlled fixed vocabulary of the functional basis. Therefore, two research questions (RQ) are examined:

RQ1. What type of contextual information should be included within function structures to ensure interpretability?

RQ2. Are there benefits of differing levels of function structure abstraction?

## 2.3 Research Task

To answer the two research questions an extensive review of the literature led to the development of two user studies. Function structures at different levels of abstraction are analyzed by mechanical engineering graduate students from which these students identified the product modeled based solely on its functional structure. Additionally, students were asked to denote what aspects of the function structures aided them in their

decision making. This information provides an in depth look at what type of contextual information is meaningful and should be included within functional modeling.



## CHAPTER 3: FRAME OF REFERENCE

Three specific functional modeling research efforts are explored through a critical literature review. First, the Functional Basis is examined to understand the motivation, applicability, and implementation of this as a controlled vocabulary for function modeling. Second, the Design Repository is evaluated as the primary implementation and archival space of function models supposedly based on the Functional Basis. Finally, newly proposed function model pruning rules are examined as a potential pruning technique to traditional function models.

### 3.1 Functional Basis

With function models providing such benefits as concept generation and product architecting assistance, researchers have identified the need for a standardized set of function related terms to allow design engineers to describe the functionality of product in a consist manner [6, 10]. For the sake of this paper the reconciled efforts of the National Institute of Standards and Technology (NIST), Missouri University of Science and Technology, and the University of Texas at Austin will be investigated and discussed. The researchers at these facilities developed a finite set of function and flow terms for functional modeling, known as the functional basis. Ultimately, the functional basis was designed to contribute to the following six areas of design (1) product architecture development, (2) systematic function structure generation, (3) archival and transmittal of design information, (4) comparison of product functionality (5) creativity in concept generation, and (6) product metrics, robustness, and benchmarks [6].

The functional basis consists of 54 functions and 45 flows, arranged in a three level hierarchy that can be used to describe the function of products in a consistent manner as well as limit functional decomposition. The function terms include terms such as branch, distribute, import, export, and store. Flow terms from the functional basis include material, mixture, hydraulic, optical, and plasma. The complete functional basis function and flow vocabulary is presented in Figure 5 and Figure 6.

**Figure 5: Functional basis function vocabulary and hierarchy**

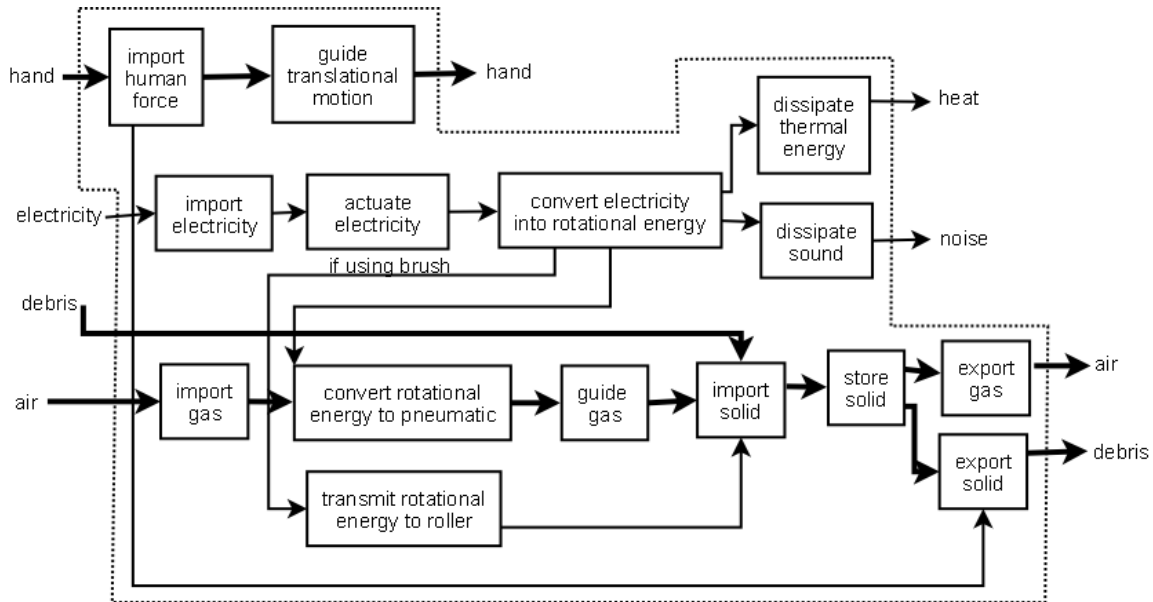
Primary	Secondary	Tertiary
Branch	Separate	Divide
		Extract
		Remove
	Distribute	
Channel	Import	
	Export	
	Transfer	Transport
		Transmit
	Guide	Translate
		Rotate
		Allow DOF
Connect	Couple	Join
		Link
	Mix	
Control Magnitude	Actuate	
	Regulate	Increase
		Decrease
	Change	Increment
		Decrement
		Shape
		Condition
	Stop	Prevent
		Inhibit
Convert	Convert	
Provision	Store	Contain
		Collect
	Supply	Supply
Signal	Sense	Detect
		Measure
	Indicate	Track
		Display
	Process	
	Process	
Support	Stabilize	
	Secure	
	Position	

**Figure 6: Functional basis flow vocabulary and hierarchy**

Primary	Secondary	Tertiary
Material	Human	
	Gas	
	Liquid	
	Solid	Object
		Particulate
		Composite
	Plasma	
	Mixture	Gas-Gas
		Liquid-Liquid
		Solid-Solid
		Solid-Liquid
		Liquid-Gas
		Solid-Gas
		Solid-Liquid-Gas
		Colloidal
Signal	Status	Auditory
		Olfactory
		Tactile
		Taste
		Visual
	Control	Analog
		Discrete
Energy	Human	
	Acoustic	
	Biological	
	Chemical	
	Electrical	
	Electro-magnetic	Optical
		Solar
	Hydraulic	
	Magnetic	
	Mechanical	Rotational
		Translational
	Pneumatic	
	Radioactive /Nuclear	
	Thermal	

The vacuum cleaner function structure, Figure 7, contains fifteen functions. Of the fifteen function instances, thirteen of the terms are found in the functional basis. Those terms include import (4 instances), export (2), convert (2), guide (2), store, actuate, and

store. The function term dissipate, which is used twice, is not captured in the functional basis. Of the 27 flow instances found in Figure 7, twelve terms are found in the functional basis. The twelve flow term instances from the functional basis are; electricity (3), gas (3), solid (3), rotational energy (2) pneumatic (energy), translation (motion). A study was conducted on the actual usage of functional basis terms according to the hierarchy, within Missouri University of Science and Technology's design repository (which will be discussed in Section 1.2) and the finding confirmed that 92% of the functional terms used in the repository are secondary [11]. Therefore, secondary terms from the functional basis were utilized in the completion of the user studies presented in this research. The first archival efforts to use the Functional Basis controlled vocabulary are embodied in the Design Repository [5].



**Figure 7: Vacuum cleaner function structure**

### 3.2 Design Repository

Motivated by the need to represent, archive, and search product design knowledge in support of engineering design activities, researchers from the Missouri University of Science and Technology (MUST) developed a web based design repository. The design repository contains functional information for over 130 reversed engineered and disassembled consumer-based products<sup>1</sup>. With engineering systems and products becoming more complex, “engineers are increasingly turning to design repositories as knowledge bases to help them represent, capture, share, and reuse corporate design knowledge”[8]. Functional information for the products is obtained by either downloading a graphical model or using the design tools to generate product matrices. Graphical functional models are available for approximately half of the products in the repository and product matrices are available for all products.

Four graphical function structures were chosen from the design repository and analyzed in the user studies presented in this thesis. The four graphical product representations analyzed were the Black & Decker rice cooker, Dewalt Sander, Shopvac vacuum cleaner, and an electric screwdriver. Reasons as to why these were chosen are discussed in Chapter 4:.

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<sup>1</sup> Repository URL: <http://function2.device.mst.edu:8080/view/index.jsp>, last accessed on December 15, 2009



**Figure 8: Black & Decker rice cooker Photo [12]**



**Figure 9: Dewalt Sander Photo [12]**



**Figure 10: Picture of Shopvac Vacuum Cleaner[12]**



**Figure 11: Picture of electric screwdriver [12]**

### 3.3 Function Structure Composition Pruning Rules

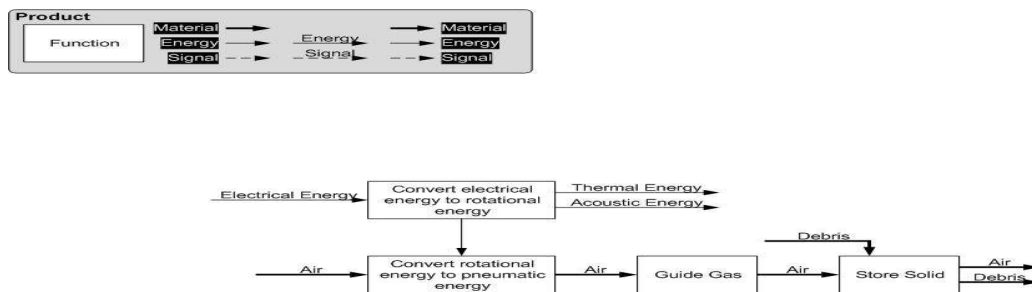
In order to reduce the level of detail, eliminate solution-specific functions, and decrease inconsistencies in the modeling of human-product interactions within reverse engineered function structures, researchers from Clemson University developed nine functional pruning rules [9]. These rules were developed by examining eighteen consumer electromechanical products from the MUST design repository. These rules are aimed at reverse engineering a function structure appropriate for the early stages in the product design process, where designers could potentially benefit more by focusing on the core functionality of the product rather than solution-specific details. For example, the function “*Transfer Electrical Energy*” refers to a wire within an existing product. While the wire is essential for the product to function, such details about a product are not important considerations on the early stage of design. The functional pruning rules developed in [10] are summarized as:

1. Remove all import and export functions.
2. Remove all channel, transfer, guide, transport, transmit, translate, rotate, and allow DOF functions referring to any type of energy, signals, or human material.
3. Remove all couple, join, and link functions referring to any type of solid
4. Remove all support, stabilize, secure, and position functions.
5. Remove all control magnitude, actuate, change, stop, increase, decrease, increment, decrement, shape, condition, prevent, and inhibit functions.



6. Remove all provision, store, supply, contain, and collect functions referring to any type of energy or signal.
7. Remove all distribute functions referring to any type of energy
8. Remove all signal, sense, indicate, process, detect, measure, track, and display functions
9. When developing function structures to adhere to the composition
10. Combine adjacent convert functions if the output flows of the first function block are identical to the inputs of the second function block.

Figure 12 is an example of applying the pruning rules to the vacuum cleaner function structure from Figure 2. The number of functions is reduced from fifteen to four, the essential flows supposedly remain within the model, and solution and assembly specific detail are eliminated from the model.



**Figure 12: Reduced Vacuum Cleaner Model after Applying Composition Rules**

### 3.4 Chapter Summary

The purpose this chapter is to review current research efforts in functional modeling, specifically the function vocabulary known as the functional basis, the design repository, and composition pruning rules. Function structures were chosen from the

design repository and translated to adhere to the claims of each research effort. These translations served as the levels of abstraction used to complete the user studies presented in this thesis. In the next chapter, Chapter 4:, the levels of abstraction are presented in further detail.

## CHAPTER 4: FUNCTION STRUCTURE ABSTRACTION LEVELS

In this study, function structures vary in abstraction in two dimensions: (1) the number of functions within the model and (2) the specificity of the terms used within the functional models. To investigate the interpretability of function structures between various levels of abstraction two user studies were conducted. The initial user study, analyzes function structures at three levels of abstraction; the DR, FB-II, and Pruned-II, which are discussed in this chapter. In order to analyze these abstraction levels three products were chosen from the design repository and translated into two additional function structures. The products chosen from the repository were the Black & Decker rice cooker, Dewalt sander, and Shopvac vacuum cleaner. As a result of the first study it was discovered that an additional abstraction level should be considered along with the initial three abstraction levels; Pruned-Free. Therefore, a refined user study was performed, and four levels of abstraction were analyzed. The initial three products were chosen and translated for the refined user study with the addition of the electric screwdriver. The four products were chosen because they are all electromechanical products that the user study participants should be familiar with.

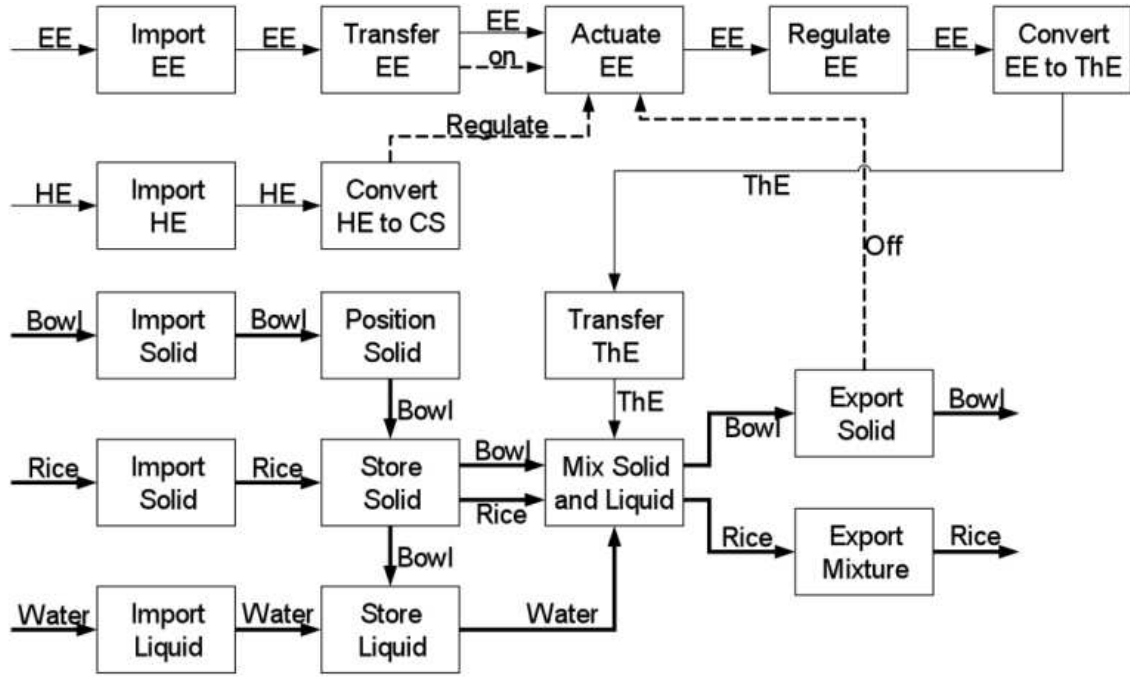
### 4.1 Translation of Function Structures between Four Levels of Abstraction

Each function structure used in the user studies is translated into different levels of abstraction. The levels are denoted as either, DR, FB-II, Pruned-II, or Pruned-II. DR represents the function structures that are directly downloaded from the Design Repository database, as discussed in Section 3.2. FB-II is represents the function

structures derived by translating the DR version to strictly follow the secondary level functions and flows of the Functional Basis vocabulary. Pruned-II represents the abstraction level obtained by reducing the FB-II function structures using the function pruning rules discussed in Section 3.3. The final abstraction level, Pruned-Free, is similar to the Pruned-II level in regards to the number functions within the model, but reverts all secondary flow terms back to the original free language terms from the DR level. These four levels of abstraction are discussed in further detail in Sections 4.1.1 - 4.1.4.

#### 4.1.1 DR Abstraction Level

The DR function structures were developed by multiple contributors, including undergraduate and graduate students [12]. While these models are predominantly constructed using secondary and tertiary level terms from the Functional Basis, approximately 25% of the flow terms in those models are natural English words [11]. The function structure of the Black & Decker rice cooker at this abstraction level is shown in Figure 13.

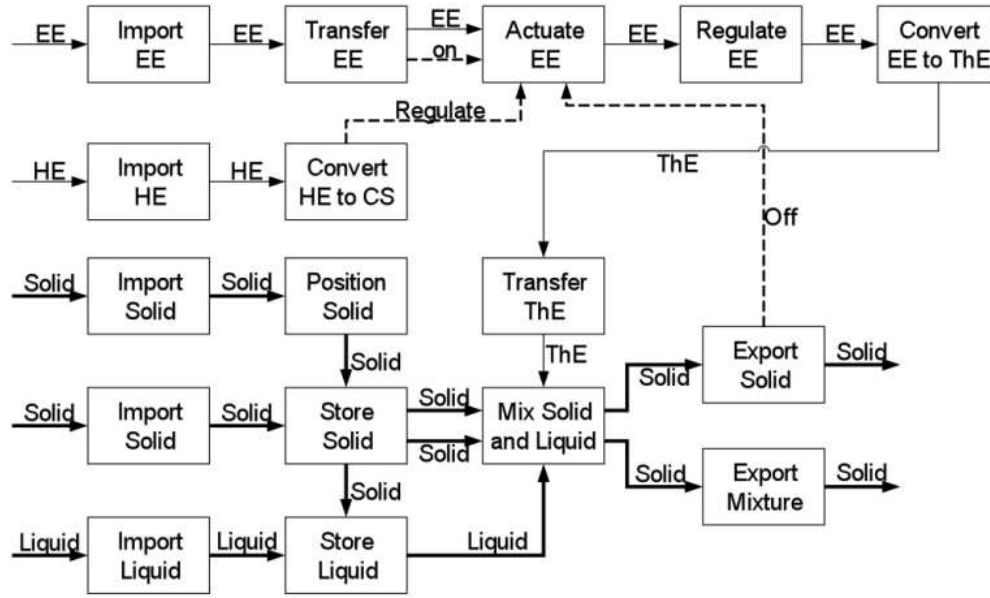


**Figure 13: Black & Decker rice cooker function structure at the DR abstraction level**

As shown in Figure 13, there are 17 functions and 27 total flows that describe the overall functionality of the product. Of the 27 flow terms, fifteen are not from the Functional Basis, for instance ‘rice’, ‘water’, and ‘bowl’. Additionally, two functions are used to describe the interaction of the product with a human, such as ‘Import HE’ and ‘Convert HE to CS’. HE and CS are the abbreviation used to represent human energy and a control signal respectively. Finally, in addition to describing the core functionality of the product, the function structure also represents the auxiliary functions within the product. Auxiliary functions are described as component specific functions [1, 2] that enable the product to perform, but are not critical to the product’s overall functionality. For example, the function ‘Transfer EE’ is corresponds to a conductor within the rice cooker, but is not a critical function that the rice cooker is used for.

#### 4.1.2 FB-II Abstraction Level

The FB-II function structures were obtained for the user study by replacing the natural English terms in the DR version of the models with appropriate terms from the secondary level of the Functional Basis, thus reducing the level of detail in the models. For instance, 'bowl', 'rice' and 'water' are replaced with 'solid', 'solid' and 'liquid' respectively. It is important to note that the number of functions and the interconnectedness of the functions at the FB-II level are exactly identical to that of the DR models; 17 functions and 27 flows. The secondary level of the Functional Basis is chosen for this level of abstraction since over 90% of the functions and flows in the function structures within the Design Repository are described with this level, indicating that this level provides a natural medium of expression for cataloging function structures through reverse engineering. The FB-II version of the rice cooker function structure is shown in Figure 14.

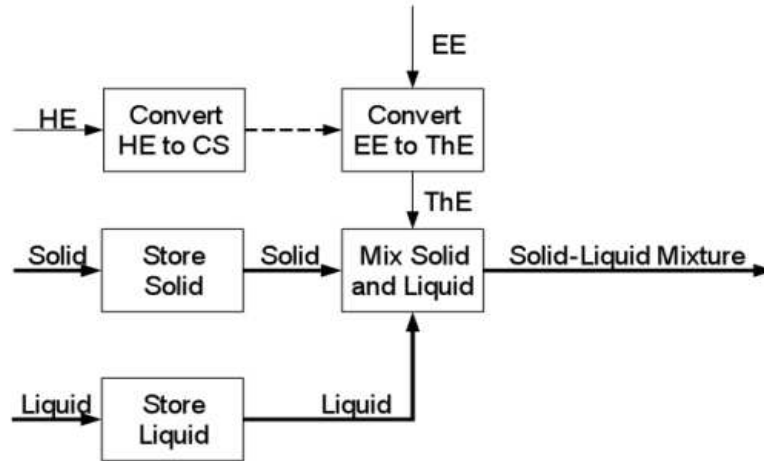


**Figure 14: Black & Decker rice cooker function structure at the FB-II abstraction level**

#### 4.1.3 Pruned-II Abstraction Level

Function structures at the Prune-II abstraction level are generated in this research by applying the pruning rules discussed in Section 3.3 to the FB-II models. Again, these rules were developed to prune the auxiliary functions from the models, which ultimately eliminate some detail from the function structures. Therefore, the number of functions in the Pruned-II version is less than the DR and FB-II versions. The pruned models utilize secondary level functional basis terms for functions and flows. The rice cooker function structure at this level is shown in Figure 15. The number of functions within the structure at the Pruned-II level is reduced from seventeen, as shown at the DR/FB-II level, to five. The pruned model eliminates all auxiliary functions from the model, but the flows across the system boundary are the same. Thus, the size of the model reduces under this

translation without any loss of essential information about the product's functionality; which is an important characteristic of the composed model [9].

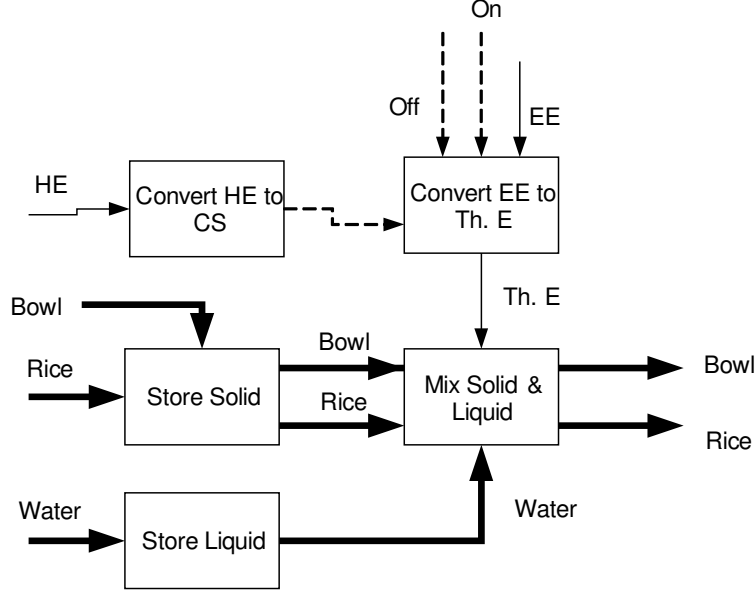


**Figure 15: Black & Decker rice cooker function structure at the Pruned-II abstraction level.**

#### 4.1.4 Pruned - Free Abstraction Level

A fourth abstraction level was discovered as a result of the initial user study. This abstraction level referred to as Pruned-Free., is constructed by taking those functions structures which adhere to the composition rules and converting the secondary flow terms back to the free language originally used in their DR function structure. Hence, the terms ‘solid’ and ‘liquid’ from the rice cooker function structure shown in Figure 15 are replaced with the free language terms ‘rice’ and ‘water’ and is shown in Figure 16. The idea behind this Pruned-Free abstraction level is to restore some information back to each products function structure, which was lost in the translation of the FB-II level to the Pruned-II level. In the case of the rice cooker the control signals (on and off) and ‘bowl’ are added back into the structure, since they were used in the original DR function structure.



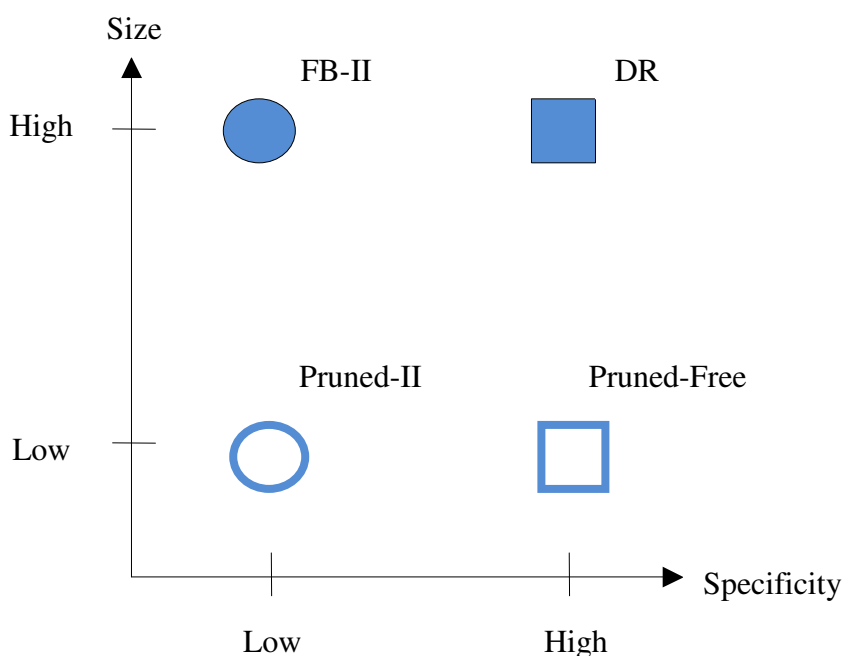


**Figure 16: Black & Decker rice cooker function structure at the Pruned-Free abstraction level**

#### 4.2 Comparison Between Four Abstraction Levels

The four function structures differ in the specificity of terms used as well as the number of functions and flows used. Figure 17 is a two dimensional model illustrating where each levels falls in terms of how abstraction is defined in this research. The DR and FB-II versions contain the same number of functions and the interconnectedness between the functions. This connection is represented by solid blue shapes in Figure 17. Thus, there is no change in size of the model under the first translation (DR to FB-II). However, the FB-II version has an assumed lower degree of specificity than the DR version due to the conversion of specific terms such as ‘rice’ to abstract terms such as ‘solid’, thus the reasoning behind the different shape representation in Figure 17 (FB-II: circle and DR: square). Further, the use of free language such as ‘rice’ captures additional context in the DR version that is lost when the model is translated to the FB-II level.

Thus, under the first translation the function structure becomes more abstract, and this abstraction is associated with the loss of specificity and context. Here abstraction generally refers to the loss of details captured in a model. However, since the FB-II version strictly adheres to the Functional Basis vocabulary, it has higher consistency and repeatability of functional description than the DR version.



**Figure 17: Two dimensional abstraction model**

The Pruned-II version of the function structure is identical with the FB-II version in terms of vocabulary, as both versions use only secondary level Functional Basis terms. Thus, both abstraction levels are illustrated as circles in Figure 17. Contextual information that was lost under the first translation is not recovered in the Pruned-II abstraction level. However, the Pruned-II version has fewer functions than the DR or FB-II levels, thus the Pruned-II circle is white and the FB-II circle is blue in Figure 17. This reduction makes the Pruned-II version even more abstract than the FB-II version. This

abstraction is associated with the reduction of model size, as opposed to the abstraction associated with the removal of context and specificity found in the first translation. The Pruned-Free version contains the same number of functions as the Pruned-II; however the Pruned-Free version can have additional flows associated with it. Some context information that was lost under the first translation is recovered within the Pruned-Free version, as abstract terms such as ‘solid’ and ‘liquid’ is converted back to ‘rice’ and ‘water’. Since this contextual information is restored the Pruned-Free level is illustrated by a square similar to the DR level.

Figure 18 is a two dimension model illustrating the number of functions and flows for each product and abstraction level used in the user studies. The model shows that the Sander and Shopvac Vacuum at the DR and FB-II level have over forty flows and more than twenty functions. The electric screwdriver representations modeled at the Pruned Free and Pruned II level both the same number of functions and flows; three and eight.

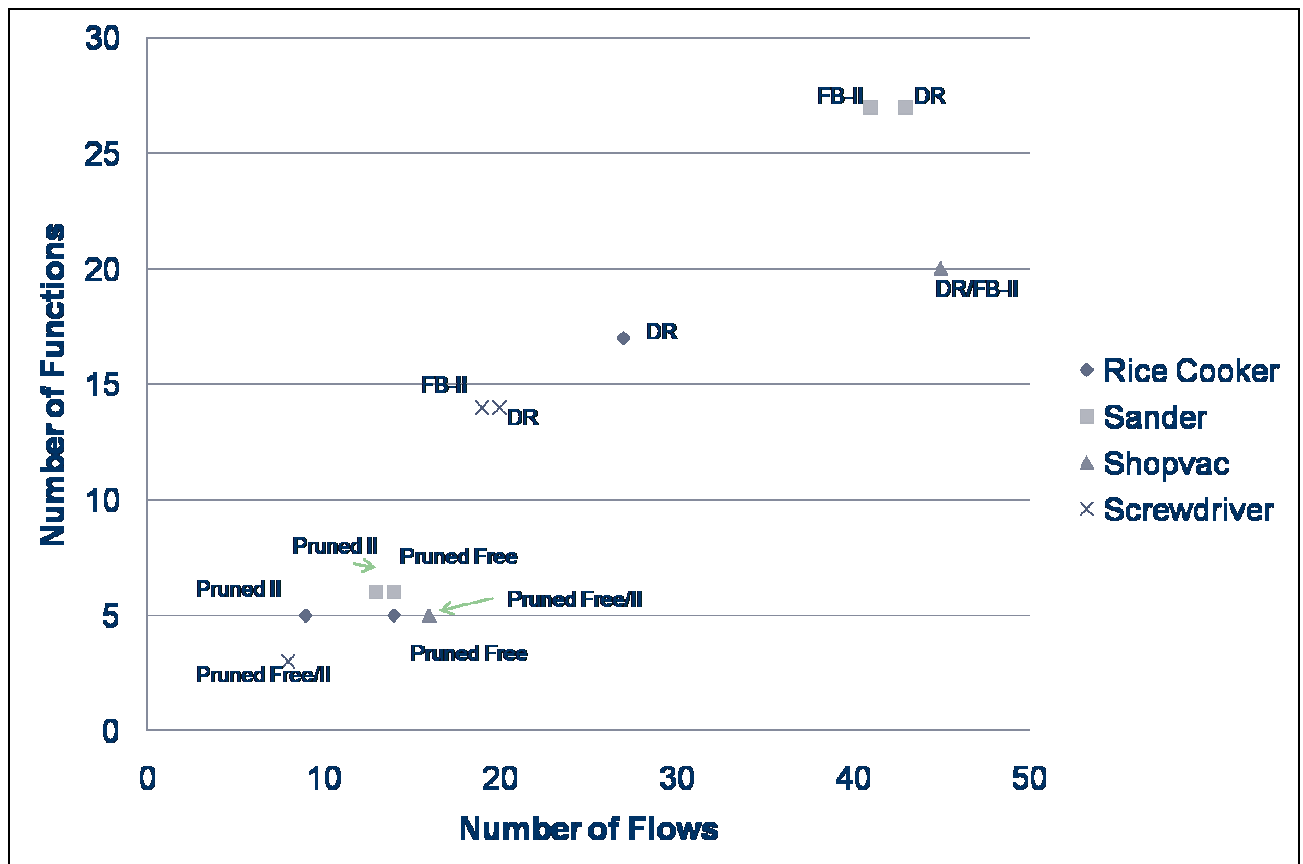


Figure 18: Functions vs. Flows for each product and abstraction level

## CHAPTER 5: INITIAL USER STUDY – INTERPRETABILITY OF THREE FUNCTION STRUCTYURES

### 5.1 User Study Methodology

Within design research it is important to understand design in order to make new tools, predict design success, monitor progress, and teach design. Aspects of design to understand include the human thought process, creativity, decision-making, collaboration, communication, representation, and reasoning. Research methods are used to calibrate values of design method variables, suggest contributing factors, and develop models to explain design. Interpretability data presented in this thesis was collected by performing two controlled user studies. User studies are a formal research method used to find areas to research, verify new methods, and compare different approaches. When utilizing the user study research method quantitative information is usually limited, but qualitative results are obtained. Therefore conducting a user study is appropriate for this research since the fundamental goal of the research is gain insight towards functional modeling. User studies have been used to study engineering design activities such as idea generation and design reviews. User study approaches typically include surveys, focus groups, interviews, observation, and diary methods [13]. In this research two user studies were conducted and this chapter presents information regarding the initial user study; such as a description of the participants and the experimental procedure.

#### 5.1.1 Participants

Sixteen mechanical engineering graduate students from Clemson University all of which who were enrolled in a graduate level design course participated in the initial user

study. The user study was performed during the students regularly scheduled class period. Therefore, the number of students chosen to participate was based on the number of student who attended class. Furthermore, to ensure environmental familiarity the participants completed the study in their engineering design course classrooms. All students had prior exposure to design theories, design methods, and design research, which includes exposure to functions and functional modeling. Issues such as gender and race were not considered in the execution of the study and data about these issues were not collected.

#### 5.1.2 Training and Normalization of Participants

On the day of the user study attempt, a ten-minute refresher presentation was presented to the participants. Within the presentation a formal definition of function, functional modeling, and function structures were given. The benefits of function models were also given, according to design literature. Slides from the presentation can be found in Appendix A. To ensure nomenclature familiarity, the Proctor Silex electric iron function structure from the design repository was presented and discussed. Once the presentation was complete, participants were given an opportunity to ask questions in regards to the presentation. After the refresher the participants were introduced to the user study, and told that they would be identifying electromechanical consumer products based on the products functional decomposition in the form of a function structure.

### 5.1.3 Experiment Packets

Each participant was given a two page packet, containing pictures of forty-eight consumer products, as illustrated in Figure 19. Page one consisted of products ‘A’ through ‘F’ and page two consisted of products ‘G’ through ‘L’.

Table 1 gives the name of each product within the Figure 19 according to the appropriate row (letter) and column (number). The purpose of the picture packets is to aid the participants in their decision making once the function structures were distributed. The picture packets are further discussed in Section 5.2. Participants analyzed the packets for approximately five minutes to ensure familiarity with each of the products. Questions did arise for some of the pictures, due to the fact the packets were printed in black and white. After questions were clarified the experiment was conducted.



**Figure 19: Pages one and two of the picture packets of product options for user study (Initial User Study)**

**Table 1: Product names for illustrations in Figure 19**

	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>
<b>A</b>	Stapler	Microwave	Electric toothbrush	Dremel
<b>B</b>	Microphone	Sparkplug	Printer	Handheld vacuum cleaner
<b>C</b>	Portable CD Player	Sander	Hair dryer	Lawn mower
<b>D</b>	Toy gun	Electric knife	MP3 player	Engine
<b>E</b>	Coffee maker	Weed trimmer	Screw driver	Pogo stick
<b>F</b>	Flywheel	Flashlight	Forklift truck	Vacuum cleaner
<b>G</b>	Wok	Sewing machine	Gaming console	Rice cooker
<b>H</b>	Electric drill	Can opener	Juicer	Blower
<b>I</b>	Shop vacuum cleaner	Toaster	Lighter	Bench grinder
<b>J</b>	Bandsaw	Nail gun	Electric pencil sharpener	Baseball shooter
<b>K</b>	Fan	Breathalyzer	Sniper rifle	Ironing machine
<b>L</b>	Shower head	Curling iron	Sprinkler	Air compressor

#### 5.1.4 Participant Worksheet Packets

Three consumer based products' function structures from the design repository were chosen and each function structure was translated according to the DR, FB-II, and Pruned-II abstraction levels discussed in Sections 4.1.1 - 4.1.3. The three products chosen for translation are the rice cooker, sander, and shopvac vacuum. Three three-page packets are developed; the packets contained each of the three products at each abstraction levels. Each packet contained different products and different abstraction levels; the reasoning behind mixing the products and abstraction level was to eliminate the opportunity for participants to develop any type of correlation between the structures within each packet. The students were given one of these three-page packets at a time and asked to identify



the product being modeled within ten minutes. Figure 20 outlines the contents of each packet. For each unidentified function structure the participants were to rely on the inputs, outputs, functions, and flows to identify the product. No black box or caption was given.

	<b>Product</b>	<b>Abstraction Level</b>
Packet 1	Rice Cooker	FB-II
	Sander	Pruned-II
	Shop Vacuum	DR
Packet 2	Sander	FB-II
	Shop Vacuum	Pruned-II
	Rice Cooker	DR
Packet 3	Shop Vacuum	FB-II
	Rice Cooker	Pruned-II
	Sander	DR

**Figure 20: Contents of experimental packets (Initial Study)**

The participants wrote the last four digits of their student ID (which is not the same as their social security number) on each function structure within their packets. In addition, participants were asked to denote what aspects of the function structures aided them in their decision making as well as the amount of time taken to identify the product. To assist the participants in capturing the time taken on each function structure, an online stopwatch was project on a screen visible to all participants. The time limit for the structure identification was fixed by the need to conduct the experiment without exceeding the time scheduled for the class. In addition, a calibration of the experiment

was conducted by two Clemson University professors, a postdoctoral researcher, and a visiting foreign student who were able to complete each of the packets in less than ten minutes.

## 5.2 Selection of Answer Choices based on Functional Similarity

Participants are required to identify a product when an unidentified function structure is presented to them. However, in order to produce observable trends of product identification, it is necessary to prevent uncontrolled variations in the participant's responses. For this reason, a preselected collection of products are offered as possible answer choices to each participant, making the problem of identification a multiple choice problem. Nevertheless, in order to prevent the answer choices from biasing the identifications, two measures are taken. First the number of options was set sufficiently high: at forty eight, and second a wide variety of produces are included in the options. The variety of these products is based on the diversity of their purpose and the function and flows within them. The forty eight product options are presented to each participant in two tables, each table on a standard 8.5"x11" sheet of paper, containing twenty-four options. These two tables are shown in Figure 19, and as shown in the figure the products are presented to the participants by pictures. Names or descriptions of these products are not included, as the same product may be known by different names by participants due to ethnicity and cultural diversity. The names are, however, furnished in Table 1.

For each of the three products whose function structures are used in the user study, the forty eight products in Table 1 are classified into two groups: functionally similar and functionally dissimilar to the product. This classification is completed to help filter out the identifications of similar products from within the collection of wrong identifications at the end of the experiment, providing a deeper insight to the interpretability of function structures under varying abstraction. Functionally similar products are of particular interest in this experiment, because with increasing abstraction, the function structures are expected to represent a wider variety of functionally similar products, due to the loss of details that belonged to a specific product and the increased focus on the essential functions that are common between similar products. In the following three paragraphs, the similar products are described and annotated, in parenthesis, with the corresponding cell location in Table 1.

A panel consisting of four mechanical engineering graduate students and a mechanical engineering professor discussed each product from the picture packets and render products similar or dissimilar to the three products used in the study. The similar products were identified based on the similarity of essential functions, essential flows, and the similarity of purpose. For example, in the case of the Black & Decker rice cooker, the list of similar products include the microwave (A2), the wok (G4), and the coffee maker (E1), as all of these products are food processing devices that accept water and food as inputs and produces cooked food or a hot beverage. All other products are considered dissimilar, as none of them meet the above criteria.

In the case of the Dewalt sander, the list of similar products includes the dremel (A4), lawn mower (C4), the drill (H1), the grinder (I4), and the pencil sharpener (J3). The dremel and grinder are similar as they are abrasive surface-polishing devices. The lawn mower is included in the list of similar products, as it is a device that removes part of the surface (grass) exposed to it, and removes the debris (cut grass) with air flow. Finally the drill and pencil sharpener are similar devices as their primary purpose is to remove material.

As for the Shopvac vacuum cleaner, the list of similar products includes the hand vac (B4), the lawn mower (C4), the vacuum cleaner (F4), and the blower (H4). The hand vac and vacuum cleaner are rendered similar as they are adaption of vacuum cleaners. The blower is similar based on the fact that it works by creating a pressure difference in air. The lawn mower is included as it involves a bag and the use of pressurized air for bagging debris, same as the Shopvac vacuum cleaner. All other products are considered dissimilar.

### 5.3 Data Collection

The function structure packets were collected at the end of each ten minute interval. This was done to ensure that participants would not refer to previous function structures to assist them in their decision making for subsequent function structures. Students were however allowed to keep the same two page packet containing the forty eight pictures of products throughout the experiment. Sample data from the study is illustrated in Table 2. The table contains the last four digits of each participant's student

ID in order to cross reference between function structures, the product they believe was being modeled in the function structure, the time taken to identify the product, and any aspects or keywords of the structures which aided them in their decision.

**Table 2: Initial User Study Data Collected Sample (All data in APPENDIX B: )**

Student	Product	Time (min:sec)	Notes
3005	Rice Cooker	3:30	Transfer of thermal energy to mixture of solid and liquid and output being rice.
3846	Rice Cooker	4:13	Input: rice and water. Output: rice.
8271	Rice Cooker	9:35	-
5869	Rice Cooker	2:47	Bowl to store rice, EE-Th.E, Export solid = separate rice from bowl
4629	Rice Cooker	-	Bowl , rice and water input
3341	Rice Cooker	-	Rice and bowl being imported and exported
1229	Microwave	6:52	Transferring the thermal energy to the solid-liquid mixture, sealed it
2438	Wok	0:45	Very specific inputs and outputs.

## 5.4 Results

The results of the user study are presented in this section. Section 5.4.1 presents the trends in exact and non-exact identification of products by the participants as function of level of abstraction of the function structures presented to them. Section 5.4.2 outlines the variety of products identified.

### 5.4.1 Exact and Non-Exact Responses

The number of exact products identified with change in abstraction level of the function structures is presented in Table 3. The left column of the table lists the three products whose function structures were used in the study: the Black & Decker rice

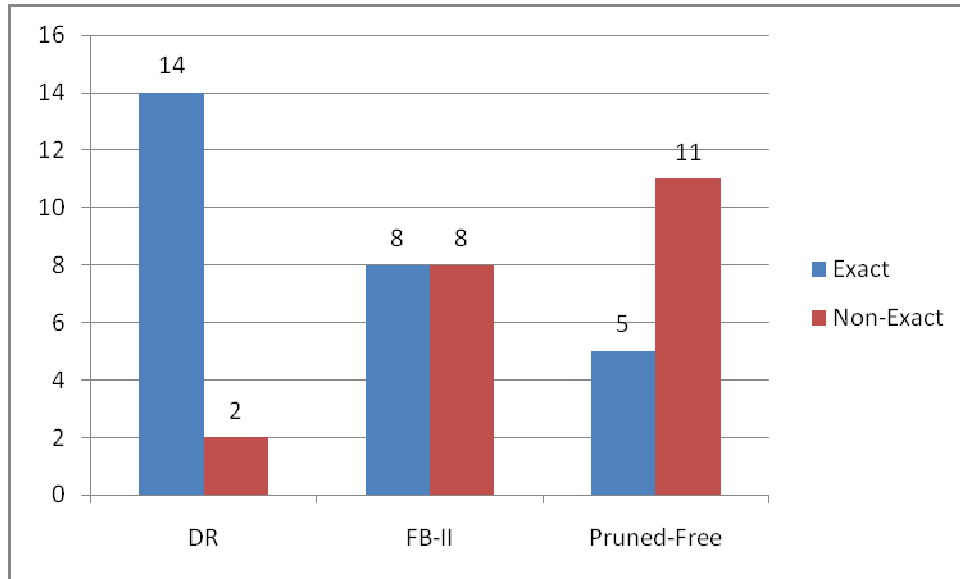
cooker, DeWalt Sander, and Shopvac vacuum cleaner. The abstraction levels, which are in perceived increasing order of abstraction as discussed in Section 4.2, are to the right of the products column. Each cell in Table 3 displays the number of students, out of the sixteen, who indentified the product when given an unidentified function structure at the corresponding abstraction level as the exact product. The number of participants returning non exact identifications for a given abstraction level of a given product can then be obtained by subtracting the number of exact identifications in the corresponding cell from sixteen.

**Table 3: Number of exact identifications of function structures based on three levels of abstraction**

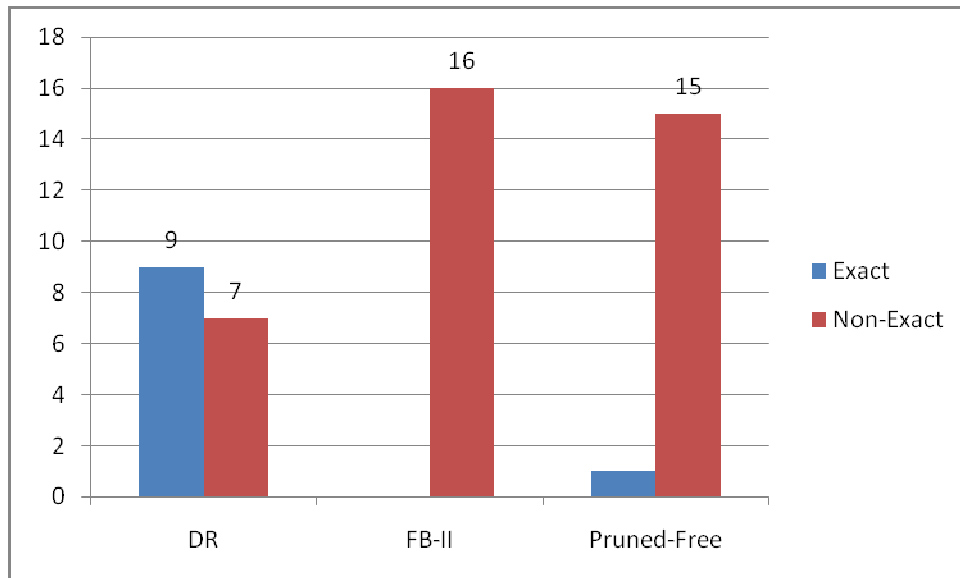
	<b>Black &amp; Decker Rice Cooker</b>	<b>DeWalt Sander</b>	<b>Shopvac Vacuum Cleaner</b>
DR	14	9	2
FB-II	8	0	0
Pruned-II	5	1	0

Based on the results in Table 3, the trend of exact and non-exact identifications with increasing degree of abstraction in the function structures are shown in Figure 21 (Black & Decker rice cooker), Figure 22 (DeWalt sander), and Figure 23 (Shopvac vacuum cleaner). In each figure, the three clusters represent the three levels of abstraction as explained in the previous paragraph. The first column (dark gray) in each cluster represents the number of participants who exactly identified the product from a function structure at a given level, while the second column (light gray) represents the number of participants who made non-exact identifications or failed to identify the product altogether, out of sixteen participants. For example, the left cluster of Figure 21

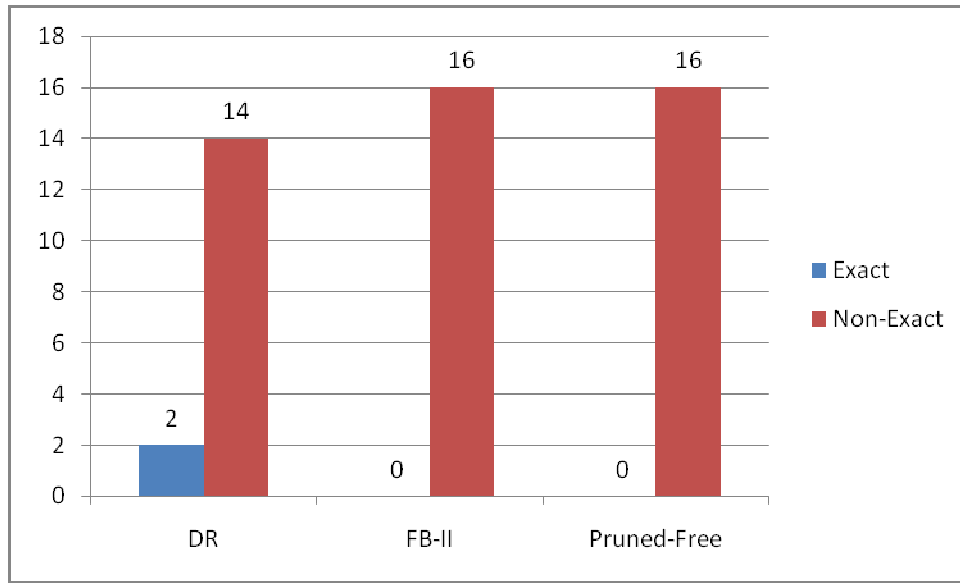
indicates that fourteen participants identified the Black & Decker rice cooker from its function structure described at the DR abstraction level as a rice cooker, while two either identified a completely different product or failed to identify a product at all.



**Figure 21: Trend in exact and non-exact product identification with increasing levels of abstraction: Black & Decker Rice Cooker**



**Figure 22: Trend in exact and non-exact product identification with increasing levels of abstraction: DeWalt Sander**



**Figure 23: Trend in exact and non-exact product identification with increasing level of abstraction: Shopvac Vacuum Cleaner**

For all three products, the DR abstraction level yielded the highest success rate in identifying the product from their function structures, compared to the other two levels of abstraction. In the case of the rice cooker (Figure 21) the number of exact identifications goes down monotonically with increasing levels of abstraction in the function structure: reducing from fourteen exact identifications at the DR level to eight at the FB-II level, and to five at the Pruned-II level. However, in the case of the sander and the vacuum cleaner (Figure 22 and Figure 23), the number of exact identifications first goes down to zero at the FB-II level, the increases marginally if at all, at the Pruned-II level. Table 4 illustrates the likelihood of exactly identifying a product exactly based on the abstraction levels used in this study. For instance, a consumer product that adheres to the DR approach of functional modeling has a 52% chance that an individual would be able to identify the product. Despite this percentage being fairly low the DR abstraction level,



which is characterized by the use of the free English language, is most easily interpretable representation out of the three levels of abstraction.

**Table 4: Likelihood of identifying a product exactly based on abstraction levels of the rice cooker, sander, and shopvac.**

DR	52.1%
FB-II	16.7%
Pruned-II	12.5%

Another trend in interpretability of function structures can be observed by examining Figure 21, Figure 22, and Figure 23 as a whole. For any given level of abstraction, the number of exact identifications reduces from the Black & Decker rice cooker, to the Dewalt sander, and from the Dewalt sander to the Shopvac vacuum cleaner function structures. For example, at the DR level, the number of successful identifications reduces from fourteen to nine to two between these models, in the aforesaid order. Similarly, the reduction is from eight to zero to zero at the FB-II level, and from five to one to zero at the Pruned-II level. Notably this trend has a correlation with the density of flow keywords present in the respective function structures. These keywords and their densities are discussed in Section 5.5.

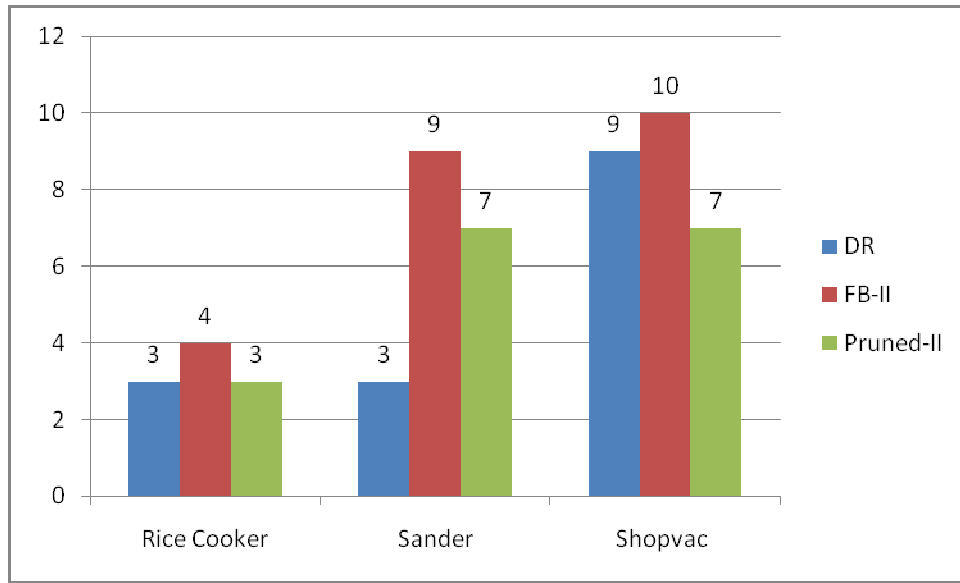
#### 5.4.2 Variation of Products Identified Based on Abstraction Level

The variation in the products identified by the participants was also recorded in the study, the results of which are presented in Table 5, which contains not only the variation of products identified but the number of students who identified a certain product. For instance in the case of the DR rice cooker function structure fourteen

students identified a rice cooker, one student identified a microwave, and one student identified a wok. For the same product at the FB-II abstraction level, eight students identified a rice cooker, five students identified a coffee maker, two students did not identify a product, and one student identified an engine. An interesting observation to note across each abstraction level is that the students identified more products at the FB-II abstraction level for the rice cooker, sander, and shop vac., which is illustrated in Figure 24. In addition, it seems as though the 'Pruned-II' abstraction level caused the most confusion, seeing that this level has the most Blank/No answer responses. Across the three products the DR has a total of three blank/no answer response which is evident with the Sander. The 'FB-II' level had a total of five blank/no answer response; the rice cooker has two blanks and the sander and shop vac. both have one blank/no answer response. The 'Pruned-II' level has a total of fifteen blank/no answer responses; the sander has seven blank responses and the shop vac. has eight.

**Table 5: Variation in student responses**

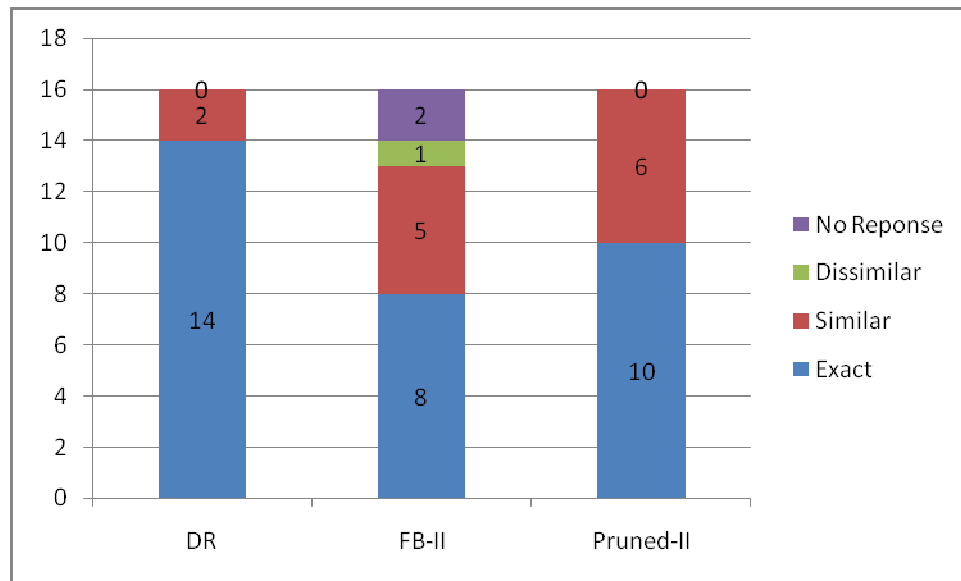
	<b>Rice Cooker</b>	<b>Sander</b>	<b>Shopvac. Vacuum</b>
<b>MUST - DR</b>	Rice Cooker (14) Microwave (1) Wok (1)	Sander (9) Grinder (4) Blank/No Answer (3)	Vacuum (3) Air Compressor (3) Shop Vac. (2) Air Blower (2) Lawn Mower (2) Wok (1) Rifle (1) Iron (1) Engine (1)
<b>FB-II</b>	Rice Cooker (8) Coffee Maker (5), Blank/No Answer(2) Engine (1)	Fork Lift (4) Vacuum (3) Hand Vac.(2) Lawn Mower (2) Machine Gun (1) Nerf Gun (1) Nail Gun (1) Air Blower (1) Blank/No Answer (1)	Fork Lift (3) Air Compressor (2) Vacuum (2) Engine (2) Blank/No Answer (2) Lawn Mower (1) Toaster (1) Wok (1) Grinder (1) Fan(1)
<b>Pruned-II</b>	Coffee Maker (10) Rice Cooker (5) Wok (1)	Blank/No Answer (7) Vacuum (4) Sander(1) Fork Lift(1) Sewing Machine (1) Lawn Mower (1) Shop Vac. (1)	Blank/No Answer (8) Vacuum (3) Microwave (1) Flashlight(1) Lawn Mower (1) Air Compressor (1) Hand Vac. (1)



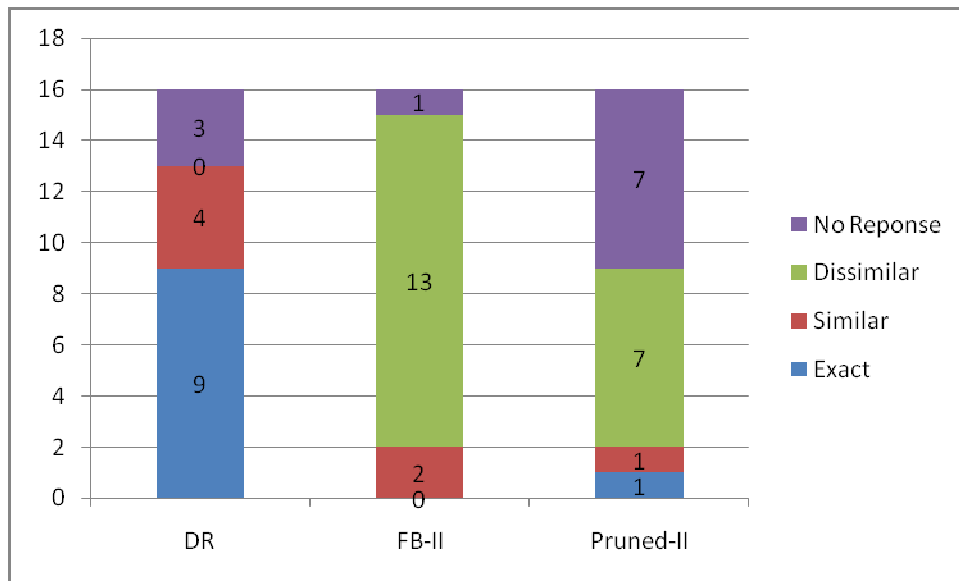
**Figure 24: Number of products identified for each product at each abstraction level.**

As discussed in Section 5.2, all products from the picture packets were classified as either being functionally similar or functionally dissimilar when compared to the three products used in the user study (rice cooker, sander, and shop vac.). The results of these classifications are illustrated in Figure 28, Figure 29, and Figure 30. Functionally similar products are of particular interest in this experiment, because with increasing abstraction, the function structures are expected to represent a wider variety of functionally similar products. Therefore exact responses and similar responses were added to together to obtain the figures below (Figure 28, Figure 29, and Figure 30). In each of these figures, the three columns represent the three abstraction levels used in the study. The height of each column represents the total number of participants in the study: sixteen. Within each column, the divisions indicate the distribution of the participants in the two categories. For example, in the second column of Figure 28, the lower division (blue) indicates that thirteen out of sixteen participants identified the product as a rice cooker or

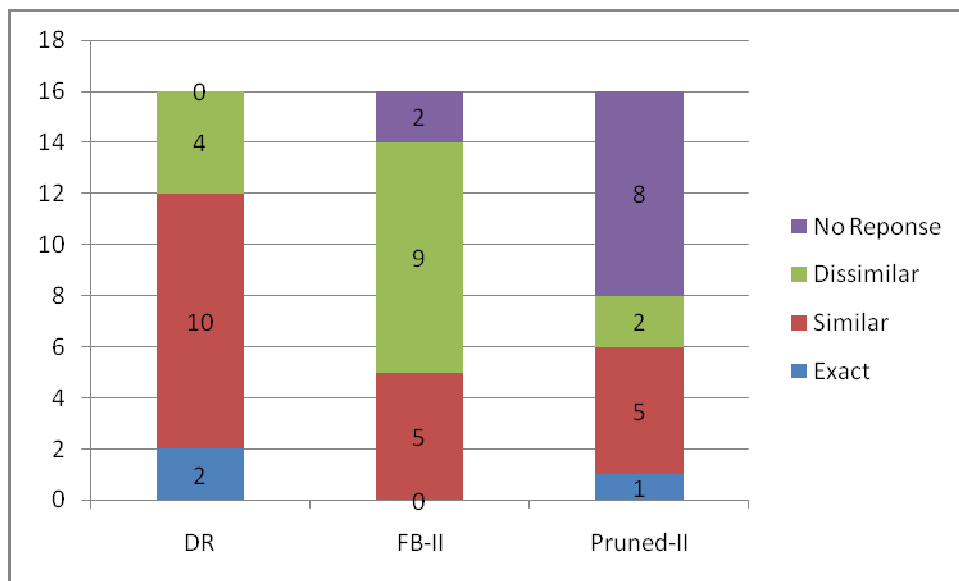
as a product that was rendered functionally similar, as discussed in Section 5.2, from the function structure at the FB-II abstraction level. The top division (red) indicates that three out of sixteen participants identified the rice cooker function structure at the FB-II abstraction level to be a product functionally dissimilar or did not identify a product at all.



**Figure 25: Variation of exact, functionally similar, functionally dissimilar, and blank responses for Black & Decker rice cooker (Initial user study results)**



**Figure 26: Variation of exact, functionally similar, functionally dissimilar, and blank responses for Dewalt Sander (Initial user study results)**

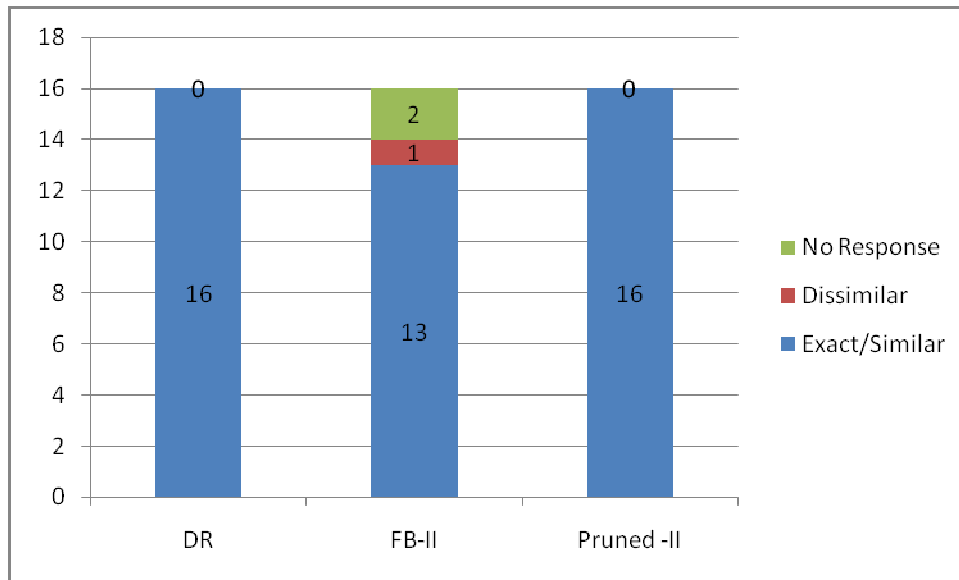


**Figure 27: Variation of exact, functionally similar, functionally dissimilar, and blank responses for Shopvac vacuum cleaner (Initial user study results)**

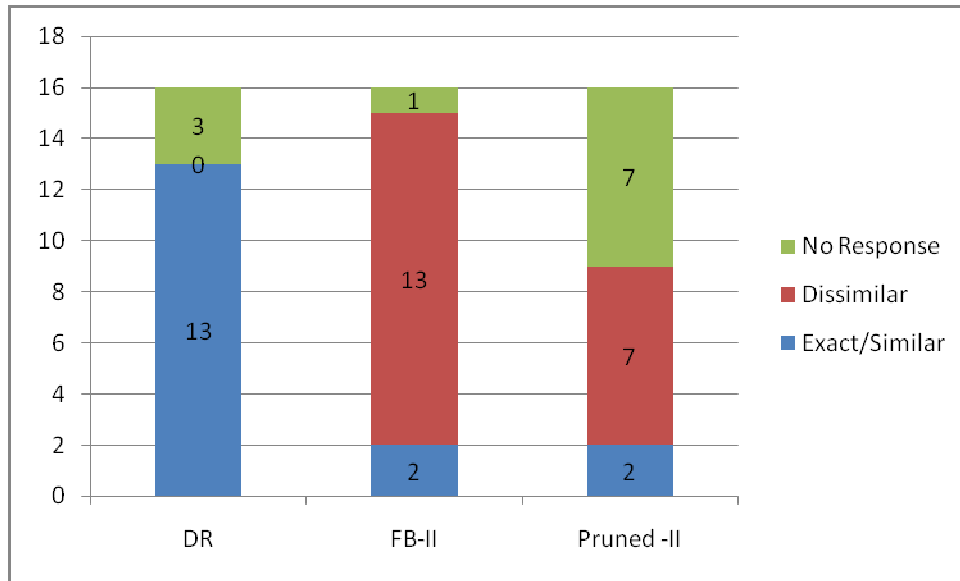
#### 5.4.3 Exact and Similar Product Responses Combined

When the total number of exact and similar identifications is examined between Figure 28, Figure 29, and Figure 30 a trend is observed: the total number reduces from

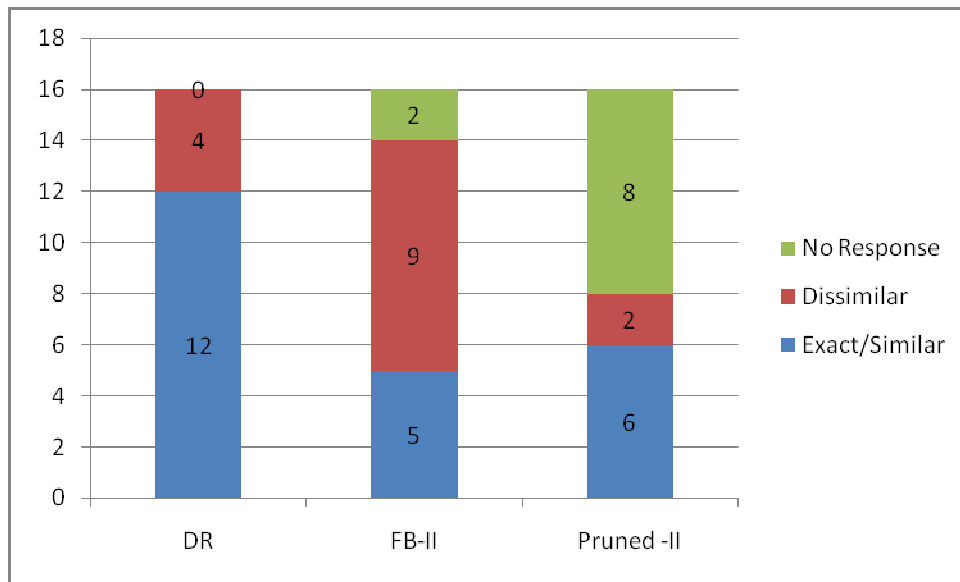
the DR level to the FB-II level, but increases or remains equal from there to the Pruned-II level. Thus, when the identification of a similar but non-exact product is considerably included as a correct identification, the interpretability of function structures reduces from the DR level to the FB-II level, but increases again from the FB-II level to the Pruned-II level. Notably, the first of these two transitions is characterized by the removal of contextual non-functional basis terms from the function structures, while the second one is obtained by eliminating auxiliary functions form the FB-II version of the models using the composition rules. Thus, apparently, the elimination of contextual information reduces the interpretability of models, whereas by cleaning up the model to retain only essential functions and flows the models interpretability is improved again.



**Figure 28: Number of exact/similar responses and dissimilar/no responses for the Black & Decker Rice Cooker at three levels of abstraction**



**Figure 29: Number of exact/similar responses and dissimilar/no responses for the DeWalt Sander at three levels of abstraction**



**Figure 30: Number of exact/similar responses and dissimilar/no responses for the Shopvac Vacuum at three levels of abstraction**

In the case of the Black & Decker rice cooker all responses were exact/similar at both the DR and Pruned-II level. As for the FB-II level the one dissimilar product was identified and two students did not identify a product at all. In regards to the DeWalt



sander, thirteen out of the sixteen participants identified exact/similar products at the DR level. At both the FB-II and Pruned-II level only two responses were exact/similar for the sander. At the FB-II level for the sander the majority of the responses given by participants were dissimilar (thirteen) and one no response. However, at the Pruned-II level both the no responses and dissimilar responses were the same, both at seven. Similar to the DeWalt sander, the shopvac vacuum had the most exact/similar responses at the DR level.

## 5.5 Observations

### 5.5.1 Participants' Notes on Enabling Features

In order to get an in-depth understanding of which factors influenced the participants' decisions during the experiments, comments were collected from the participants on the worksheets. In the case of the rice cooker function structure at the DR abstraction, all fourteen exact response participants indicated that the use of the words 'rice', 'water', and 'bowl' helped them identify the product as a rice cooker. In the case of the same function structure at the FB-II abstraction level, the eight exact response participants mentioned the following features in the model provided hints leading to correct identification: the mixing between a solid and a liquid, the output material being only a solid, and the conversion of electrical energy to thermal energy. However, four participants who identified the product as a coffee maker also used the mixing between a solid and a liquid and the conversion of electrical energy to thermal energy as their hints. Notably, these two functions are similar between the rice cooker and the coffee maker, as the coffee maker mixes coffee (solid) with milk or water (liquid), and consumes electrical

energy for its operation similar to the rice cooker. In the case of the rice cooker function structure at the Pruned-II abstraction level; all five of the participants who gave exact responses mentioned that the mixing of a solid and a liquid helped them identify the product.

In the case of the Dewalt sander function structure at the DR abstraction level, all nine participants who gave exact response noted that the use of specific terms such as ‘sandpaper’, ‘wood’, and ‘debris’ helped them identify the product. In the FB-II abstraction level of this model, all sixteen participants failed to identify the product exactly and there was no noticeable trend in their notes. In the case of the Pruned-II version of the same model, only one participant identified the sander as a sander, thus a trend in comments could not be established.

In the case of the Shopvac vacuum cleaner function structure at the DR abstraction level, only two of the sixteen participants identified exactly, and only one of them left a note, mentioning that the use of pneumatic energy was used as a hint to identify the product. In the two higher abstraction levels of this product none of the participants identified the product exactly, and there is no noticeable trend in their notes.

Notably, all the keywords that helped the participants to identify the correct products are non-Functional basis terms borrowed from the natural English dictionary. Each term describes a flow, as opposed to a function, in the respective function structures, and each can be reorganized to be a part of the environmental context of the respective products. For example, rice, water, and the bowl are part of the rice cooker’s

context. The same argument applies to sandpaper, wood, and debris in the case of the sander, and to air and debris in the case of the vacuum cleaner. Thus, the representation of environmental context significantly helped product identification.

### 5.5.2 Flow Keyword Density

In order to further investigate the effect of the contextual keywords to the interpretability of function structures, the number of instances of these keywords is counted for all three function structures at the DR abstraction level. Then the density of these keywords in the respective function structures is analyzed. The results of this analysis are shown in Table 6.

**Table 6: Flow Keyword Density Analysis**

	Black & Decker rice cooker	Dewalt Sander	Shopvac vacuum cleaner
# of keyword instances	15	11	8
# of flows in the model	27	44	45
Density of flow keywords	0.56	0.25	0.18

In Table 6, the second, third, and fourth columns represent the three products whose function structures are used in the experiment. The second row indicates the total number of times a contextual keyword is used as a flow label in the respective models. For example, in the case of the Black & Decker rice cooker, the three keywords, ‘rice’, ‘water’, and ‘bowl’, are used in the model on a total of fifteen flow labels. Similarly, the keywords ‘sandpaper’, ‘wood’, and ‘debris’ are used in a total of eleven flow labels in the Dewalt sander model. In the case of the Shopvac vacuum cleaner, the keywords ‘debris’ or ‘air’ are found in eight flow labels. In the last case, however, each instance of flows

labeled as ‘debris and air’ is counted as one occurrence. Also, the four instances of ‘air’ at the bottom of the function structure, used to represent the cooling action are not counted, as these instances are not related to the debris removal function of the product. The third row of Table 6 shows the total number of flows in the respective models. For example, the Black & Decker rice cooker function structure at the DR abstraction level has 27 flows in total. The fourth row in the table shows the density of flow keywords in each model, by taking the quotient of the number of flow keywords to the total number of flows. The density of keywords is 56%, 25%, and 18% for the rice cooker, the sander, and the vacuum cleaner models.

Referring back to the trends of exact product identifications a correlation can be observed between the density of flow keywords in the model and the interpretability of the model. As the keywords density goes down from 56% to 25% to 18% from the rice cooker, to the sander to the vacuum cleaner function structures, the number of exact identifications goes down from fourteen, to nine, to two, respectively. Thus, a higher density of contextual keywords in the function structures seems to have a positive effect on its interpretability. Again, the DR abstraction level is characterized by its use of free language, and was shown to be the easiest abstraction level to interpret, irrespective of the product being modeled.

## 5.6 Conclusions from Initial User Study

In this section, the results and observations from Section 5.4 and Section 5.5 are summarized. Four key conclusions are identified from this user study:

1. *The use of free language improves the human interpretability of function structures compared to controlled vocabularies.*
2. *The representation of environmental context improves the human interpretability of function structures.*
3. *Abstraction of function structures generally reduces the uniqueness of the model, but promotes the description of the class of functionally similar products, rather than a specific one.*
4. *The two mechanisms of functional abstraction, namely elimination of context and elimination of auxiliary functions and flows are essentially different; despite the similarity of their end effects on function structures noticed in conclusion #3. They do not represent intensities of the same effect. Rather, they are two independent ways of achieving functional abstraction.*

A detailed discussion of the first three conclusions is found in Chapter 7. Conclusion #4 serves as the primary motivation for conducting a refined user study. This refined study analyzes a fourth abstraction point that was not considered in the initial study. The fourth abstraction level is referred to as Pruned-Free, which was discussed in Section 4.1.4. This abstraction level is similar to that of the Pruned-II level in regards to the number of functions however; the specificity of terms used at the Pruned-II level is similar to that of the DR abstraction level. The refined user study is discussed in Chapter 6.



## CHAPTER 6: REFINED USER STUDY – INTERPRETABILITY OF FOUR FUNCTION STRUCTURES.

The refined user study procedure is similar to that of the initial user study. The primary difference between the refined and the initial user study is the analysis of a fourth abstraction level, known as Pruned-Free, which is discussed in Section 4.1.4. Since an additional abstraction level is being analyzed, an additional product's function structure from the MUST design repository must be utilized. The structure chosen was the electric screwdriver. The rice cooker, shopvac vacuum, and sander function structures from the initial user study were reused in this user study. The purpose of this user study is still to ascertain the interpretability of functional representations at various levels of abstraction.

### 6.1 Participants

Participants were chosen based on their enrollment in a graduate mechanical engineering design course taught at Clemson University. Eighteen students participated in the refined user study attempt. Therefore, the number of students chosen to participate is based on the number of students who attended class on the day of the study. All students had prior exposure to design theories, design methods, and design research, which includes exposure to functions and functional modeling. Furthermore, to ensure environmental familiarity, the participants completed the study in their engineering design course classroom. Issues such as gender and race were not considered in the implementation of the study and data about these issues were not collected.

## 6.2 Training and Normalization of Participants

Similar to the initial user study, a ten minute presentation was presented to the new user study participants. This presentation the same presentation presented to the first user study participants, and can be found in APPENDIX A: . Overall the presentation defined function in engineer design, outlined the benefits of functional modeling, and provided a function structure example (Proctor Silex iron) from the design repository for discussion. After the presentation, the participants were given an opportunity to ask any questions pertaining to the presentation.

## 6.3 Experiment Packets

Participants were given a two page picture packet containing forty-eight electromechanical consumer products. The picture packets from the initial user study are modified since twelve of the products that were used did not come from the design repository and therefore replaced. Removed products include the microphone (B1), sparkplug(B2), MP3 player (D3), engine(D4), flywheel (F1), forklift(F3), gaming console (G3), baseball shooter (J4), sniper rifle (K3), shower head(L1), sprinkler (L3), and the air compressor (L4), as seen in Table 1. These products were replaced with the electric screwdriver (B1), electric shaver (B2), salad shooter (D3), electric knife (D4), circular saw (F1), nail gun (F3), game controller (G3), popcorn popper (J4), CD player (K3), kettle (L1), can opener (L3), and a cotton candy maker (L4). The revised picture packet is illustrated in Figure 31, along with the name of each product in Table 7. Students were given a few minutes to ask any questions about the pictures contained within the picture packets to ensure familiarity. The picture packets were printed in color



for the refined user study, and fewer questions arouse regarding what was being illustrated in the packets, compared the initial user study.



**Figure 31: Pages one and two of the picture packets of product options for refined user study**

**Table 7: Product names for illustrations in Figure 31**

	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>
<b>A</b>	Stapler	Microwave	Electric Toothbrush	Dremel
<b>B</b>	Electric Screwdriver	Electric Shaver	Printer	Handheld Vacuum Cleaner
<b>C</b>	Disposable Camera	Sander	Hair dryer	Lawn Mower
<b>D</b>	Toy Gun	Electric Knife	Salad Shooter	Engine
<b>E</b>	Coffee Maker	Weed Trimmer	Paintball Gun	Pogo Stick
<b>F</b>	Circular Saw	Flashlight	Nail Gun	Vacuum cleaner
<b>G</b>	Wok	Sewing Machine	Gaming console	Rice Cooker
<b>H</b>	Electric Drill	Can opener	Juicer	Blower
<b>I</b>	Shop Vacuum cleaner	Toaster	Lighter	Bench Grinder
<b>J</b>	Band Saw	Can Opener	Electric Pencil Sharpener	Popcorn Popper
<b>K</b>	Fan	Breathalyzer	Portable CD Player	Ironing Machine
<b>L</b>	Kettle	Curling Iron	Electric Jar Opener	Cotton Candy Machine

#### 6.4 Participant Worksheet Packets

The purpose of this user study is to investigate the interpretability of four function structure representations. Therefore, four eight-page worksheet packets were developed each containing function structures for a shop vacuum, rice cooker, sander, and electric screwdriver at four different levels of abstraction, which are discussed in Sections 4.1.1 through 4.1.4. Since an additional product and abstraction level is added to this user study, participants are asked to provide more information in regards to their decision making. For every two pages of the packets information is to be extracted about one product. In other words, the first two pages of the eight page packet is for data collection

of a one product, pages three and four for a second product, pages five and six for a third product, and pages seven and eight pertain to a fourth product. The type of information to be collected from each product include, the last four digits of the participants student ID number, the amount of time taken to identify the product being modeled from the function structure (start and finish), confidence in identification response, and what information from the function structure served as a primary aid in their decision. The participant worksheet packets used in the study can be found in APPENDIX D:

To assist with time keeping an online digital clock was projected on a screen visible to all participants. The participants confidence level was measured on a scale from one to five; with one indication low confidence/not sure and five indicating extremely confident. Students are given twelve minutes to complete the contents of each of the four worksheet packets. The time limit is fixed by the need to conduct the experiment without exceeding the time scheduled for the class. Time evidence from the initial user study suggested, that this is indeed a sufficient amount of time for participants to complete the worksheets.

The products and abstraction levels were mixed between worksheet pages in each of the four packets, in attempt to eliminate the opportunity for participants to develop any type of correlation between the function structures within each packet. Table 8 illustrates the contents of each packet.

**Table 8: Contents of experimental packets for Group A and B respectively**

	Product	Abstraction Level
<b>Packet 1</b>	Rice Cooker	Pruned-II
	Sander	DR
	Electric Screwdriver	Pruned-Free
	Shopvac	FB-II
<b>Packet 2</b>	Rice Cooker	DR
	Shopvac	Pruned-Free
	Sander	Pruned-II
	Electric Screwdriver	FB-II
<b>Packet 3</b>	Shopvac	Pruned-II
	Rice Cooker	FB-II
	Electric Screwdriver	DR
	Sander	Pruned-Free
<b>Packet 4</b>	Shopvac	DR
	Electric Screwdriver	Pruned-II
	Sander	FB-II
	Rice Cooker	Pruned-Free

#### 6.5 Selection of Answer Choices based on Functional Similarity

The same guidelines apply to the selection of answers based on functional similarity as discussed in Section 5.2, for the refined user study. Again, a product is considered functionally similar to another, in this research, if it achieves the same high level purpose. Products within the picture packets were classified as functionally similar or functionally dissimilar to the four products being analyzed. In this research products that are functionally similar refers the completion of a high level. To recap, in the case of the Black & Decker rice cooker, the list of similar products include the microwave (A2), the wok (G4), the coffee maker (E1), and the kettle (L1) as all of these products are food processing devices that accept water and food as inputs and produces cooked food or a hot beverage. All other products are considered dissimilar, as none of them meet the

above criteria. In the case of the Dewalt sander, the list of similar products includes the dremel (A4), lawn mower (C4), the drill (H1), the grinder (I4), and the pencil sharpener (J3). The dremel and grinder are similar as they are abrasive surface-polishing devices. The lawn mower is included in the list of similar products, as it is a device that removes part of the surface (grass) exposed to it, and removes the debris (cut grass) with air flow. Finally the drill and pencil sharpener are similar devices as their primary purpose is to remove material. As for the Shopvac vacuum cleaner, the list of similar products includes the hand vac (B4), the lawn mower (C4), the vacuum cleaner (F4), and the blower (H4). The hand vac and vacuum cleaner are rendered similar as they adapt to vacuum cleaners. The blower is similar based on the fact that it works by creating a pressure difference in air. The lawn mower is included as it involves a bag and the use of pressurized air for bagging debris, same as the Shopvac vacuum cleaner. All other products are considered dissimilar. Finally, products rendered similar to the electric screwdriver are the dremel (A4) and drill (H1). These products are considered similar to the electric screwdriver in that they are all mechanisms that apply torque by rotating the tip. All products rendered similar to the four controlled products used in the refined user study are illustrated in Table 9.

**Table 9: Products rendered similar to the four products used in refined user study.**

	<b>Rice Cooker</b>	<b>Sander</b>	<b>Shopvac Vacuum</b>	<b>Electric Screwdriver</b>
<b>Similar Products</b>	Coffee Maker Kettle Microwave Wok	Dremel Lawn Mower Grinder Pencil Sharpener	Handvac Vacuum Cleaner Lawn Mower Blower	Dremel Drill

## 6.6 Data Collection

Each eight page worksheet packet is collected at the end of twelve minute interval. This was done to ensure participants did not refer to previous function structures to assist them in their decision making for subsequent function structures. Students are, however, allowed to keep the same two page packet containing the forty eight pictures of products throughout the experiment.

Sample data from the study is illustrated in Table 10. The table contains (1) the last four digits of each participant's student ID in order to cross reference between function structures, (2) the product they believe was being modeled in the function structure via produce name and produce ID (based on picture packet), (3) the time taken to identify the product, (4) participant confidence level regarding their decision, and (5) any aspects or keywords from the structure which aided them in their decision. As seen in Table 10 some students did not complete the worksheets in their entirety denoted by dashes in Table 10. Examples can be found with student 2458 who do not denote the amount of time taken to identify the fourth product in his packet, which he recognized as a carpet vacuum and rated his confidence as a two. Another example is seen with student 8193 who left the final two pages of his packet completely blank.

**Table 10: Refined User Study Data Collected (APPENDIX C: )**

<b>ID</b>	<b>Model</b>	<b>Product Name</b>	<b>Product ID</b>	<b>Time Taken (mins)</b>	<b>Confidence</b>	<b>Comments</b>
2458	G1	Coffee Maker	E1	0:57	3	Only one machine mixed solid. Heat applied. Solid is grounds, understood as coffee.
	G2	Sander	C2	1:25	4	Sander paper is used. Wood is involved.
	G3	Electric Screwdriver	B1	0:33	5	Screw, electric energy used to guide solid
	G4	Carpet Vacuum	F4	-	2	Solid plus gas. Solid is separated. Pneumatic energy is used.
1378	G1	Coffee maker	E1	1:11	2	Solid liquid mixture
	G2	Hand saw	F1	0:39	3	Output wood. Hand movements
	G3	Screwdriver	B1	0:19	4	Input EE. Output screw and mechanical energy
	G4	Sander	C2	5:44	1	Vague guess
8193	G1	Coffee Maker	E1	0:38	2	EE to Th.E. Store/Mix. Liquid/solid. Made less confident because thermal energy is not shown added to the liquid as expected. Also don't expect solid/liquid mixture leaving
	G2	Sander	C2	2:08	5	"Hand" used to manipulate solid. "wood" and "sandpaper" gave it away.
	G3	Electric Screwdriver	B1	0:48	5	"screw"
	G4	-	-	-	-	-

## 6.7 Results

The results of the refined user study are presented in this section. Section 6.7.1 presents the trends in exact and non-exact identifications of the rice cooker, sander, shopvac, and electric screwdriver function structures by the participants based on level of abstraction. Section 6.7.2 presents the variation of products identified. Section 6.7.3 presents the similar product response data. Section 6.8.1 presents an overview of the participant's notes on enabling features that assisted them in their decision on identifying the products described by each function structure. Section 6.8.2 outlines the amount of time taken by participants as well as their confidence level regarding their decisions.

### 6.7.1 Exact and Non-Exact Responses

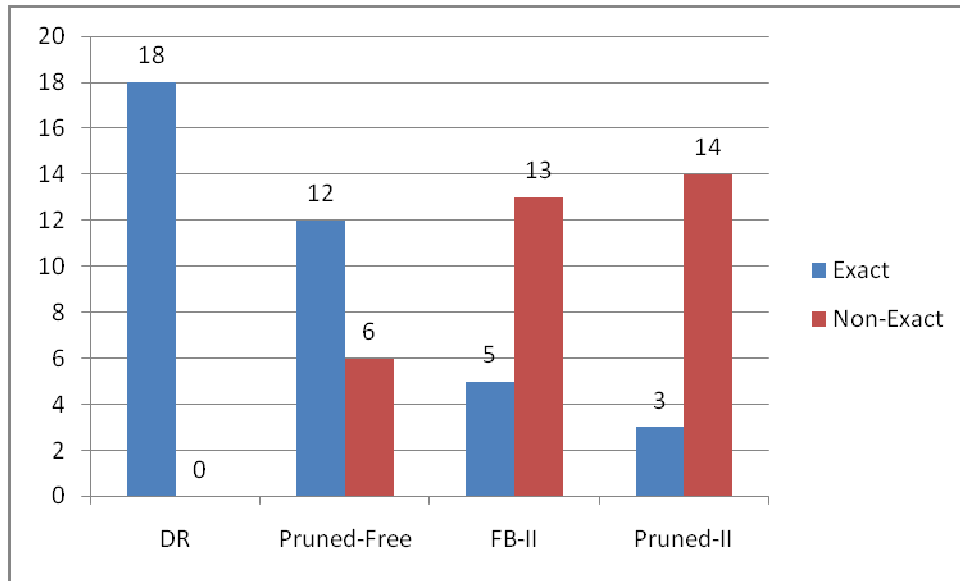
The number of students who identify the rice cooker, sander, shopvac vacuum, and electric screwdriver function structures exactly according to each abstraction level is presented in Table 11. The left column of the table lists the four abstraction levels; which are in perceived increasing order of abstraction, as discussed in Section 4.2, as you move down the column. The top row shows the four products whose function structures were used in the study. Each cell in Table 11 shows the number of students, out of the eighteen, who identified the product exactly based on its function structure. The number of participants returning non exact identifications for a given abstraction level of a given product can then be obtained by subtracting the number of correct identifications in the corresponding cell from eighteen.



**Table 11: Number of correct identifications of products based on the function structure level of abstraction**

	Black & Decker Rice Cooker	DeWalt Sander	Shopvac Vacuum Cleaner	Electric Screwdriver
DR	18	11	3	11
Pruned-Free	12	12	6	11
FB-II	5	0	0	0
Pruned-II	3	2	3	1

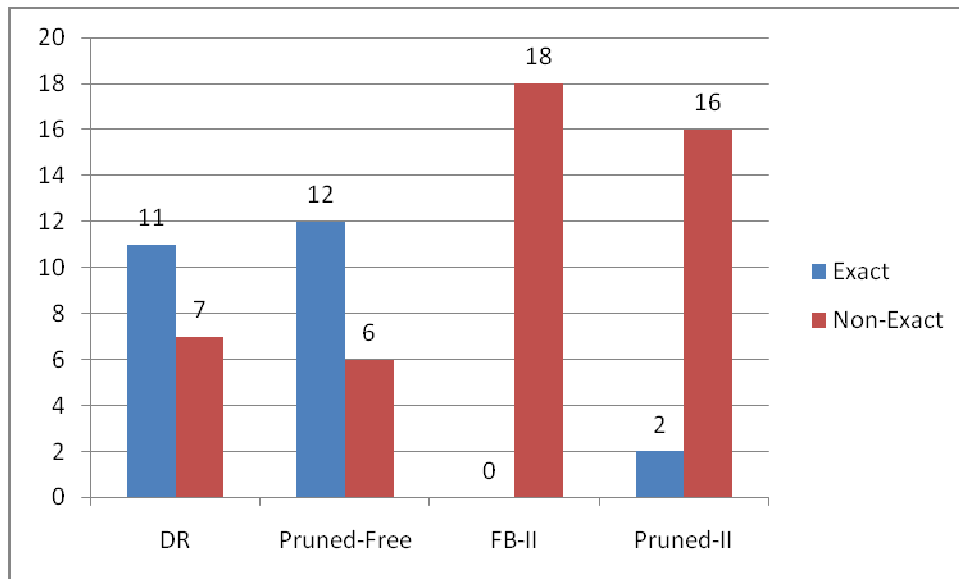
A graphical representation of the results from Table 11 for each product is illustrated in Figure 32 (Black & Decker rice cooker), Figure 33 (Dewalt sander), Figure 34 (Shopvac vacuum cleaner), and Figure 35 (electric screwdriver). In each figure, the four two-bar clusters represent the four levels of abstraction. The first column (dark gray) in each cluster represents the numbers of participants who correctly identified the product from a function structure at a given level, while the second column (red) represents the number of participants who made an did not make an exact identification or failed to identify a product altogether. For example, the left cluster of Figure 32 indicates that all eighteen participants correctly identified the Black & Decker rice cooker from its function structure which adhered to the development rules that corresponds to that of the DR abstraction level. Twelve participants indentified the rice cooker modeled at the Pruned-Free level exactly and six students identified the product as something else.



**Figure 32: Trend in exact and non-exact product identification based on perceived increasing levels of abstraction: Black & Decker rice cooker**

The results of the Black & Decker rice cooker at the DR, FB-II, and Pruned-II abstraction levels are similar to those of the initial user study, in that the number of exact product identification goes down monotonically as the level of abstraction increases; reducing from eighteen successful identifications at the DR level to twelve at the Pruned-Free level to five at the FB-II, and to three at the ‘Pruned-II’ level of abstraction. As stated in Section 4.2, it is hypothesized that the DR level was the less abstract level of abstraction due to its larger size and usage of free language and the Pruned-II level to be the most abstract level due to the reduction in number of function and conformity to a function based vocabulary. This is evident from Figure 32 in that all students identified the rice cooker exactly at DR and Pruned-II level had the most non-exact responses; over 80% of the students identified the rice cooker as something other than a rice cooker.

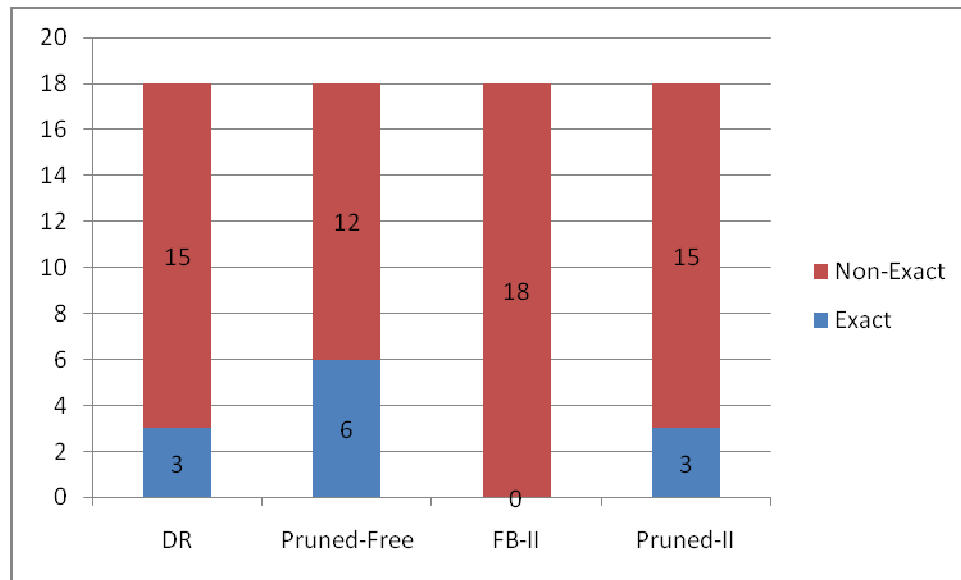
Results from the DeWalt sander at the DR, FB-II, and Pruned-II level are similar to the initial user study as well. For both the initial and refined user study more students were able to identify the sander at the DR level compared to the FB-II and Pruned-II levels. In addition, no one was able to identify the sander at the FB-II level. At the Pruned-II level a little over 12% of the responses were exact. However, the sander results tend to slightly suggest that the Pruned-Free abstraction level has a higher degree of interpretability, seeing that the Pruned-Free level has an additional exact response.



**Figure 33: Trend in exact and non-exact product identification based on perceived increasing levels of abstraction: Dewalt Sander**

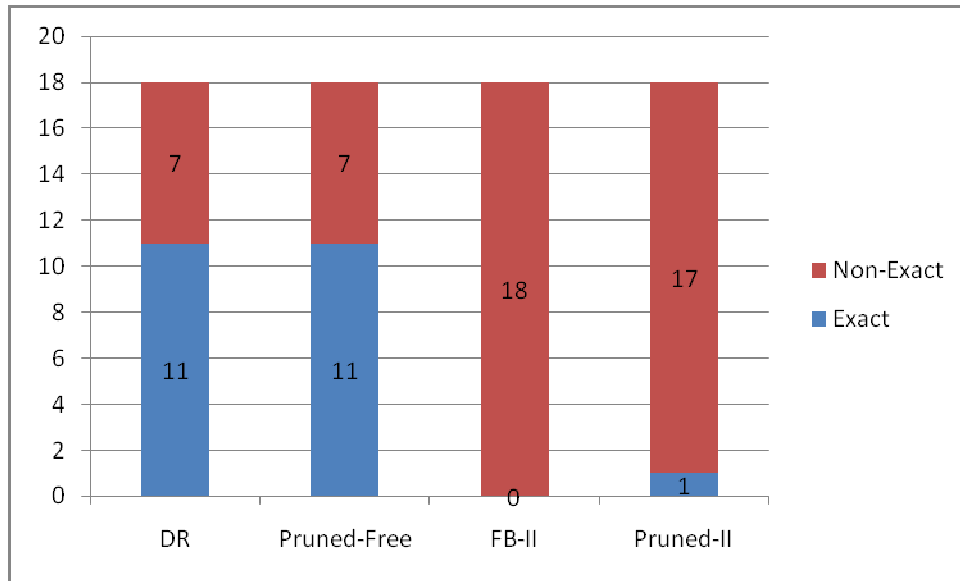
When comparing the refined and initial user study results for shopvac vacuum cleaner the results at the FB-II abstraction level are the same; no one was able to identify the shopvac vacuum exactly. The results of the shopvac are illustrated in Figure 34. The results suggest that the Pruned-Free abstraction level has a highest degree of interpretability, seeing that the Pruned-Free level had twice as many exact identifications

than the DR level. Again, similar to the results of the sander, this violates the initial claim that the Pruned-Free level is slightly more abstract than the DR level.



**Figure 34: Trend in exact and non-exact product identification based on perceived increasing levels of abstraction: Shopvac vacuum cleaner**

The results of the electric screwdriver, illustrated in Figure 35, suggest that the Pruned-Free abstraction level is just as interpretable as the DR level. In addition, the Pruned-II level may not be more abstract than the FB-II.



**Figure 35: Trend in exact and non-exact product identification based on perceived increasing levels of abstraction: Electric Screwdriver**

Overall the DR abstraction level yielded the highest success rate, in regards to indentifying the rice cooker, sander, shopvac vacuum, and electric screwdriver exactly from their function structures, compared to the other three levels. This claim is based on the fact that out of the seventy-two responses for all four products at one level, forty-three of those responses, or approximately 60%, were exact identifications as to what the product was being modeled at the DR level. Responses from the Pruned-Free level for each product were fairly close to the results of the DR level at 57%. Products modeled at the FB-II level had the lowest success rate at indentifying the exact product; at roughly 7%. The chances of identifying a product based on the four abstraction level and four products used in this user study are illustrated in Table 12.

**Table 12: Chances of identifying a product exactly based on abstraction levels used in study.**

DR	59.72%
Pruned-Free	56.94%
FB-II	6.94%
Pruned-II	12.50%

#### 6.7.2 Variation of Products Identified Based on Abstraction Level

The products identified by participants of the refined user study are presented in Table 13. The left column of the figure represents each of the four abstraction levels and the top row represents each product used in the study. Within the cells are the products identified by the participants as well as the number of participants who identified that particular product. For instance, the function structure for the sander at the DR abstraction level; eleven students identified a sander, two students identified a circular saw, two students identified a band saw, and three different students identified a vacuum cleaner, pencil sharpener, and grinder.

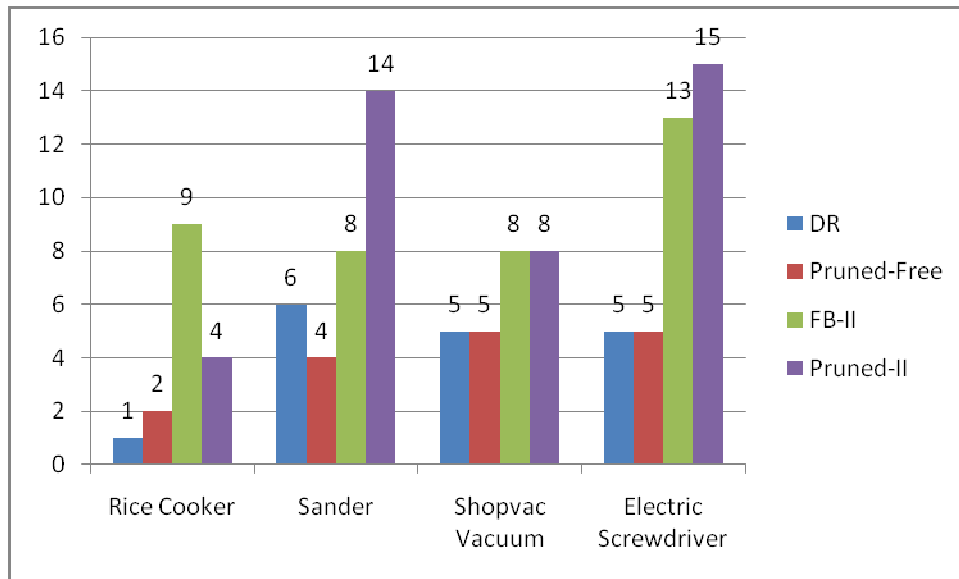
**Table 13: Variation in student responses of refined user study**

	<b>Rice Cooker</b>	<b>Sander</b>	<b>Shopvac Vacuum</b>	<b>Electric Screwdriver</b>
<b>DR</b>	Rice Cooker (18)	Sander (11) Circular Saw (2) Band Saw (2) Vacuum Cleaner (1) Pencil Sharpener (1) Grinder (1)	Hand vac (6) Vacuum Cleaner (5) Shopvac Vacuum (3) Sander (3) Coffee Maker (1)	Electric Screwdriver (11) Drill (3) Nail Gun (2) Toaster (1) No Response (1)

<b>Pruned-Free</b>	Rice Cooker (12) No Response (6)	Sander (12) Circular Saw (3) Band Saw (2) No Response (1)	Shopvac Vacuum (6) Vacuum Cleaner (5) Hand vac (5) Sander (1) Lawn Mower (1)	Electric Screwdriver (11) Drill (3) Nail Gun (2) Paintball Gun (1) No Response (1)
<b>FB-II</b>	Rice Cooker (5) Coffee Maker (5) Wok (2) No Response (2) Microwave Oven (1) Popcorn Popper (1) Cotton Candy Machine (1) Washing Machine (1)	No Response (6) Band saw (2) Coffee Maker (2) Nail Gun (2) Vacuum Cleaner (2) Dryer (1) Pencil Sharpener (1) Blower (1) Hand vac (1)	Vacuum Cleaner (6) No Response (4) Dryer (2) Hand vac (2) Juicer (1) Lawn Mower (1) Sander (1) Grinder (1)	Salad Shooter (4) No Response (3) Jar Opener (1) Sewing Machine (1) Toaster (1) Nail Gun (1) Band saw (1) Camera (1) Pencil Sharpener (1) Popcorn Popper (1) Can Opener (1) Paintball Gun (1) Candy Machine (1)
<b>Pruned-II</b>	Coffee Maker (12) Rice Cooker (4) Juicer (1) Wok (1)	Sander (2) Nail Gun (2) Coffee Maker (2) No Response (2) Jar Opener (2) Pencil Sharpener (1) Hair Curler (1) Weed Whacker (1) Breathalyzer (1) Juicer (1) Candy Machine (1)	Vacuum Cleaner (8) Shopvac (3) Hand vac (2) Popcorn Popper (1) Blower (1) No Response (1) Salad Shooter (1) Candy Machine (1)	Nail Gun (2) Circular Saw (2) Pencil Sharpener (2) Electric Screwdriver (1) Jar Opener (1) Toaster (1) Band saw (1) CD Player (1) Salad Shooter (1) No Response (1) Candy Machine (1) Lawn Mower (1) Can Opener (1)

		Blower (1)		Microwave (1)
		Shopvac (1)		Motor (1)

Figure 36 represents the actual number of different products identified for each product at the four abstraction level used in the refined study. The results of the rice cooker suggest that the rice cooker's function structure at FB-II was more abstract compared to the other three levels due to the fact participants identified nine different products at this level. The Pruned-II level was more abstract when compared to the DR, Pruned-Free, and FB-II level for both the sander and electric screwdriver seeing that fourteen products were identified for the sander and fifteen for the electric screwdriver.

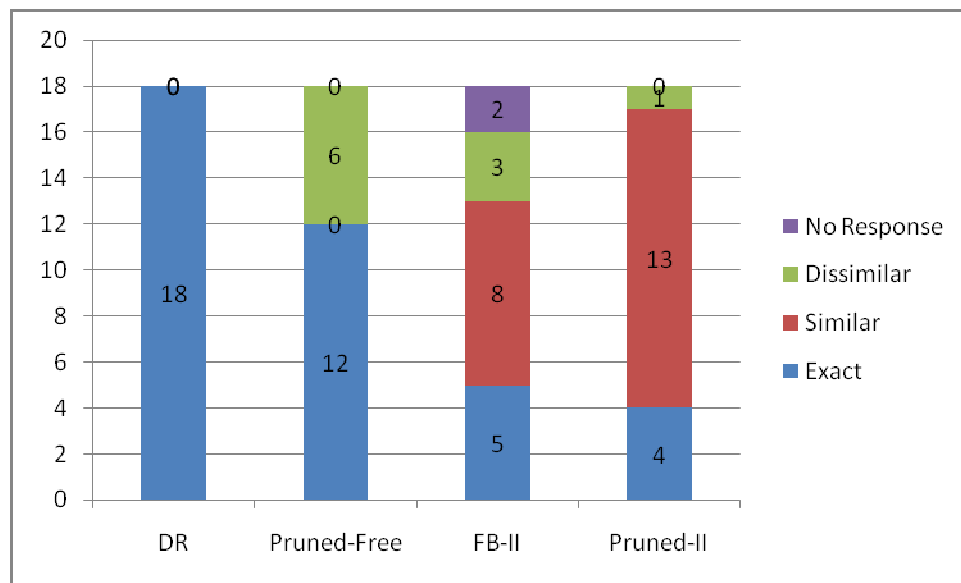


**Figure 36: Number of different products identified for each product used in the refined user study at each level of abstraction**

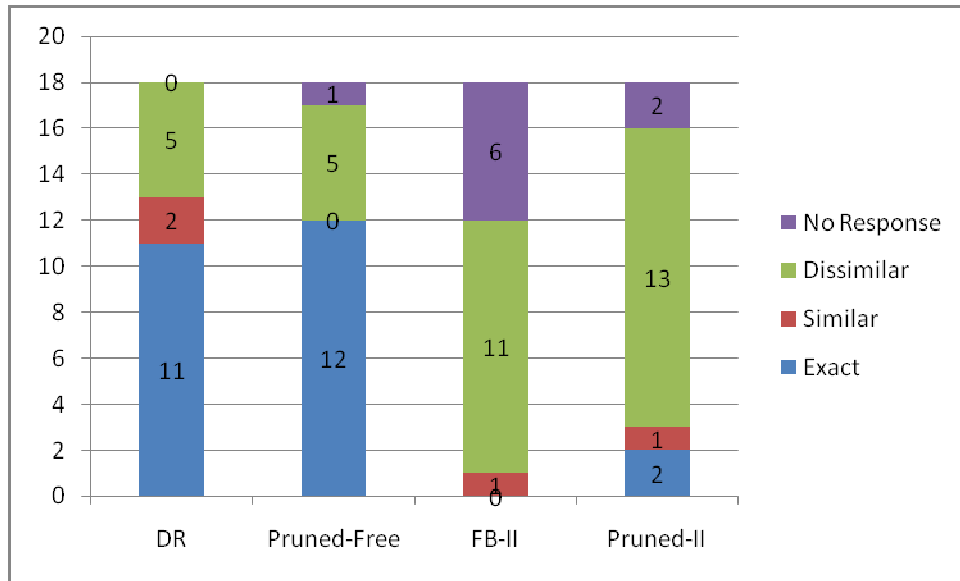
As discussed in Section 6.5 each product illustrated in each participant's picture packet is classified as functionally similar or functionally dissimilar to the four products used in the user study. The classification of the responses for the Black & Decker rice cooker, Dewalt sander, Shopvac vacuum cleaner, and electric screwdriver are shown in



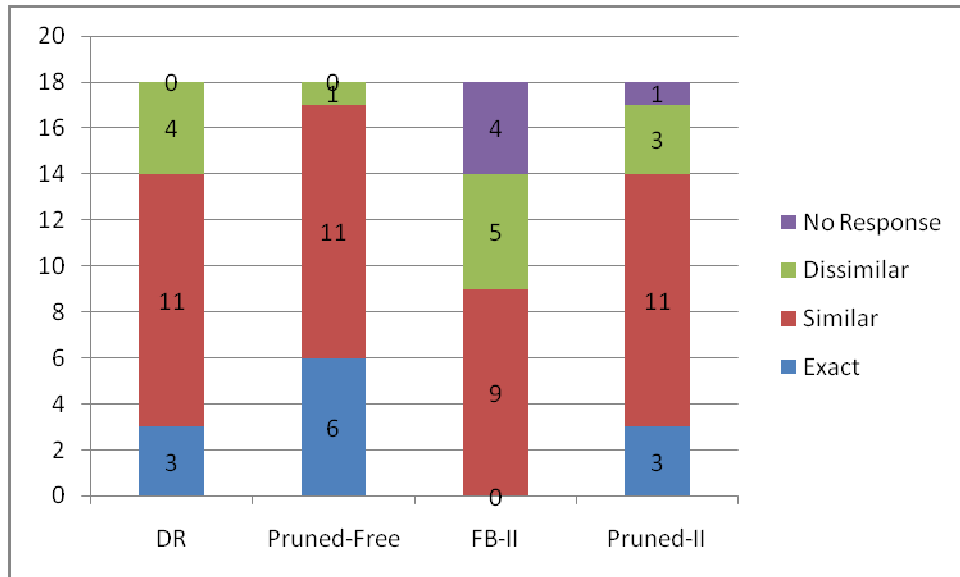
Figure 37, Figure 38, Figure 39, and Figure 40 respectively. Each of the four figures has four columns representing the results at the DR, Pruned-Free, FB-II, and Pruned-II, abstraction levels. Each abstraction level column is divided by four different colors; blue, red, green, and purple; which represent exact responses, functionally similar responses, functionally dissimilar responses, and no response respectively. For instance, in Figure 37 at the FB-II level for the rice cooker; five students identified the function structure exact, eight students identified similar responses, three students identified functionally dissimilar products, and two students did not respond at all.



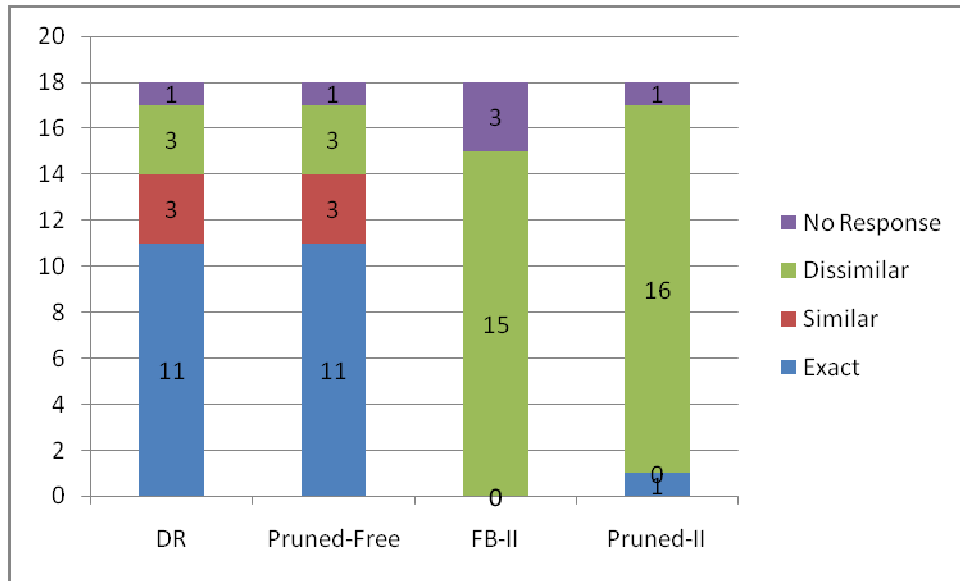
**Figure 37: Variation of exact, functionally similar, functionally dissimilar, and blank responses for Black & Decker rice cooker (Refined user study)**



**Figure 38: Variation of exact, functionally similar, functionally dissimilar, and blank responses for Dewalt Sander (Refined user study)**



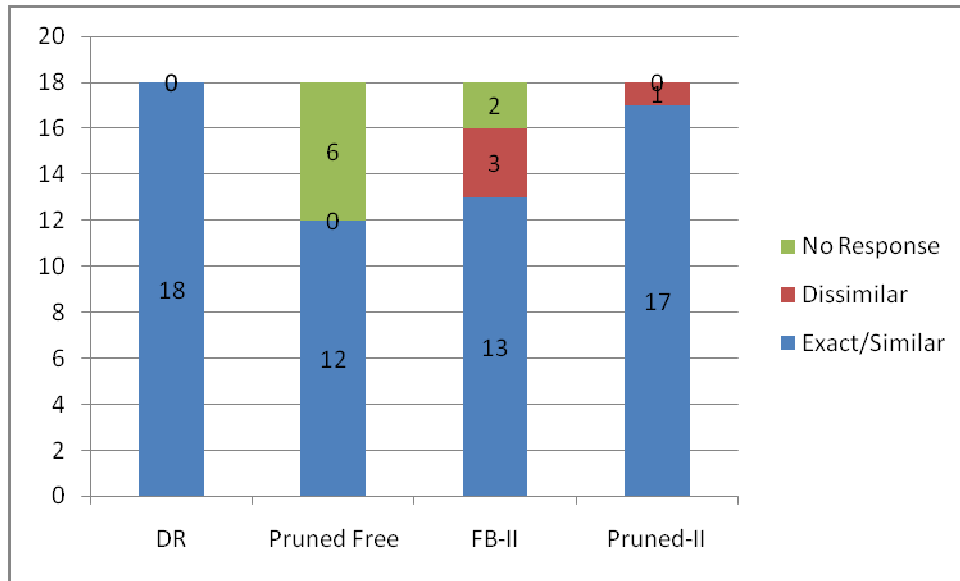
**Figure 39: Variation of exact, functionally similar, functionally dissimilar, and blank responses for Shopvac vacuum cleaner (Refined user study)**



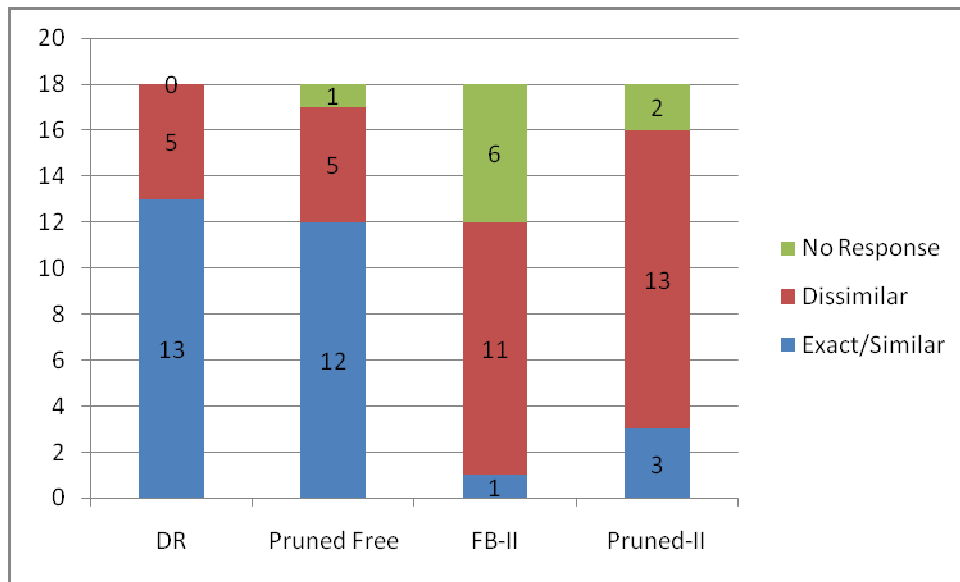
**Figure 40: Variation of exact, functionally similar, functionally dissimilar, and blank responses for electric screwdriver (Refined user study)**

### 6.7.3 Exact and Similar Product Responses Combined

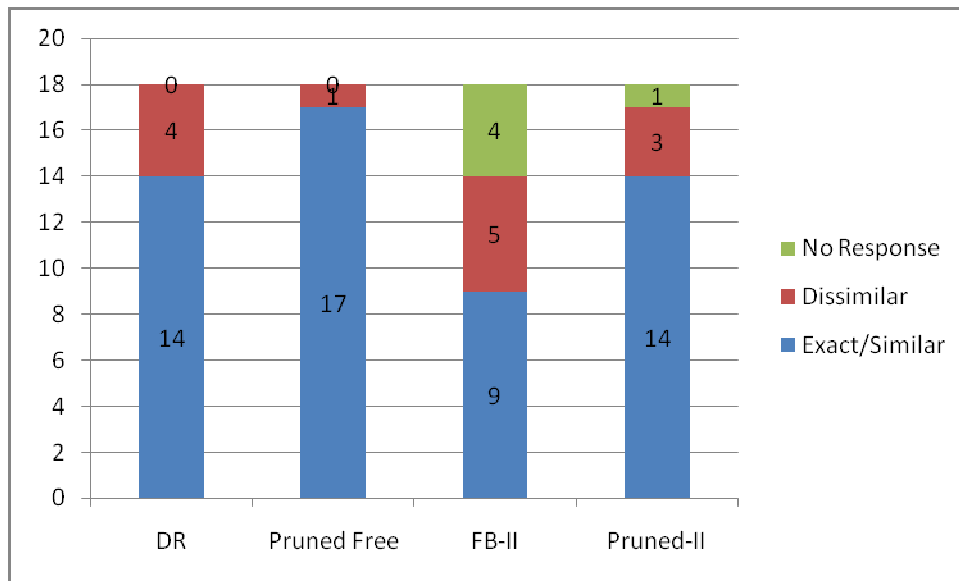
As mentioned in Section 2.1, function structure interpretability is defined on two levels. The first level is an individual's ability to identify the exact product for which a function structure was originally created. The second level is an individual's ability to identify products that accomplish the same high level purpose or are functionally similar, though not the exact product. Therefore, to analyze the true interpretability of the four function structure abstraction levels used in this study, the exact and similar responses given by the participants are combined and shown in Figure 41, Figure 42, Figure 43, and Figure 44.



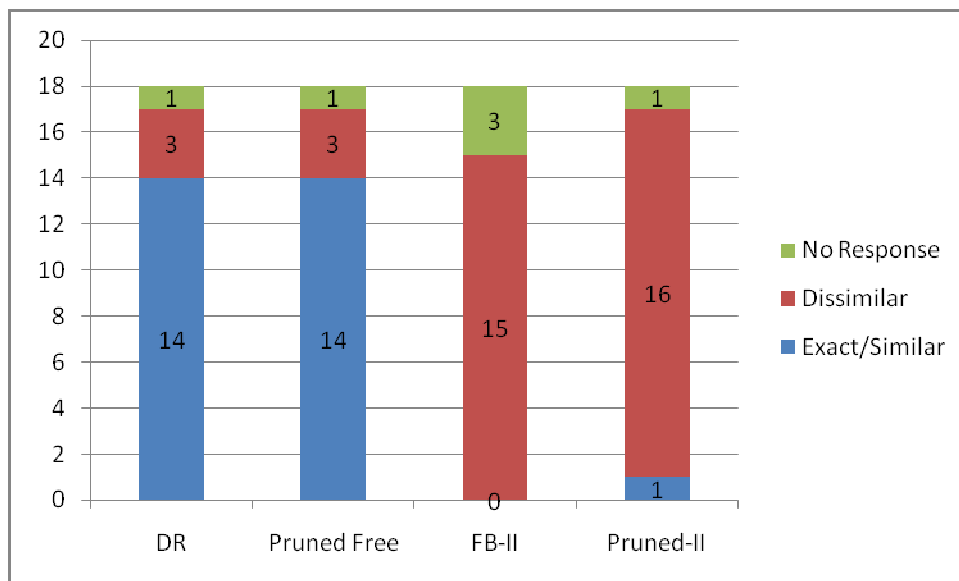
**Figure 41: Number of exact/similar, functionally dissimilar, and no response given for Black & Decker Rice Cooker (Refined user study)**



**Figure 42: Number of exact/similar, functionally dissimilar, and no responses given for Dewalt Sander (Refined user study)**



**Figure 43: Number of exact/similar, functionally dissimilar, and no response given for Shopvac Vacuum cleaner (Refined user study)**



**Figure 44: Number of exact/similar, functionally dissimilar, and no responses given for electric screwdriver (Refined user study)**

## 6.8 Observations

This section presents observations that were made by reviewing the notes participants left on their worksheets, the average time taken by participants to identify a product, and the average confidence in their decisions.

### 6.8.1 Participants' Notes on Enabling Features

In order to gain additional insight regarding the interpretability of the function structures analyzed in the study, participants indicated what aspects of each function structure aided them in their decision making on their experiment worksheets. For the rice cooker function structure at the DR abstraction level, all eighteen participants indicated that the use of the word 'rice' was a key contributor towards identifying the product. The same is true for the twelve out of eighteen participants who identified the rice cooker exactly at the Pruned-Free abstraction level. The remaining six student's responses were blank and the participants did not provide comments at all. At the FB-II level for the rice cooker, students relied primarily on the functions within the model to identify products. One participant's comments read "Import solid, storing and mixing with liquid to get a solid output using EE and HE" and this participant identified a microwave. A majority of participants, fifteen out eighteen, indicated that the mixing portion of the rice cooker function structure at the Comp. Rule level aided them in their decision making.

In the case of the Dewalt Sander at the DR level all participants denoted that the use of either sand paper or wood aided them in their decision making. Even though the

all students alluded to the specificity of terms, six different products were identified from the function structure at the DR level. One participant identified a Bandsaw his comments read as follows: “(1) Processing wood and separating debris. (2) EE input, guiding with hand. (3) Using Pn.E to separate debris.” At the Pruned-Free level a similar trend is observed; seventeen out of eighteen students denoted that the free language terms such as sandpaper, wood, and debris from the function structure aided them in their decision. Seven out of eighteen participants did not leave comments for the sander function structure at the FB-II level, thus not providing a response to the identification of the product modeled in the function structure. For those participants who did leave comments it seems as though the term ‘solid’ everyone’s primary focus and trying to decipher what was being represented. Students alluded to the solid being an article of clothing, a blade, wood, dirt, and even a pencil. At the Pruned-II level it seems as though participants regained their confidence, seeing that only two students did not identify a product. One of the students who did not answer commented, “The function model has too few details making it ambiguous.” However for those who did respond seem to focus on the separating and storing of the solid, which ultimately rendered fourteen unique responses from the participants.

As for the Shopvac vacuum function structure at the DR level the majority of the participants, fifteen, indicated that the use of the debris provided the most help towards identifying a product. In addition many students pointed out that the usage of the word hand or human energy contributed to their responses. One participant wrote on his worksheet that the terms debris, air, and hand led him to identifying a hand vacuum.

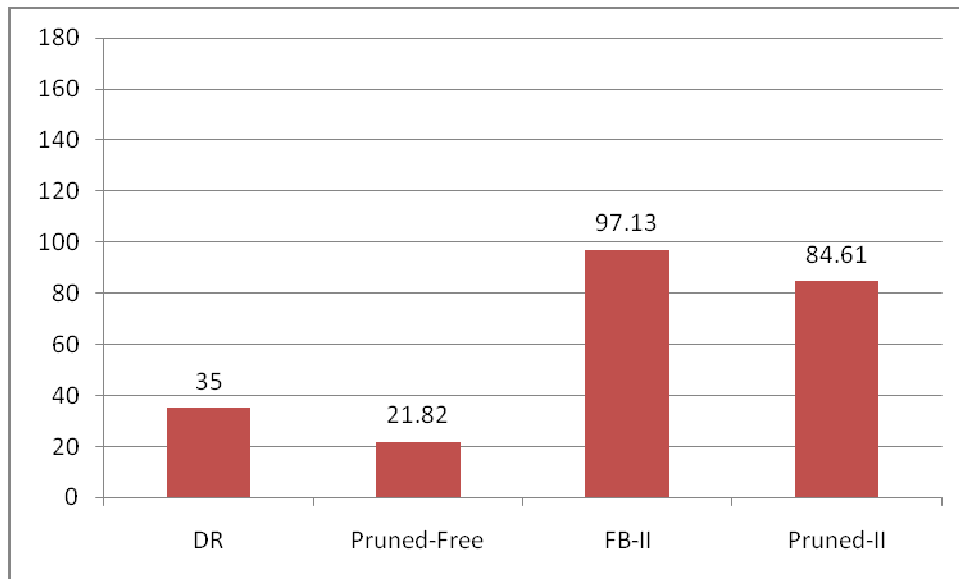
Another participant specified that, “air and debris as input giving debris as output and using of the hand to guide solid” motivated his decision in choosing the sander as the product being modeled. The comments from the Pruned-Free abstraction level are similar to that of the DR in the usage of free language motivated most decisions. At the FB-II level many students referred to the ‘solid-gas mixture’ within model as the key factor in their decision and the half of students did identify vacuums just not the shopvac vacuum cleaner. Also, two students interpreted this mixture to be articles of clothing in a dryer. At the Pruned-II level more vacuuming devices were identified and a common comment amongst participants was the storing of a solid and the input of solid-gas mixture motivated their decision.

In the case of the electric screwdriver at the DR level the majority of participants claimed that the usage of the word ‘screw’ aided them in their decision. In addition, ‘guiding of the hand’ within the structures motivated many students as well. The human interaction, ‘guiding of the hand’, was so influential that seventeen out of the eighteen of the function structure identifications provided by students were handheld devices; the electric screwdriver, a hand drill, and a nail shooter. Comments at Pruned-Free level were similar to the DR, so much so, that the identification of exact, similar, dissimilar and blank responses came out exactly the same. At the FB-II and Pruned-II levels participants seemed to have focused much of their attention on the solid and the ‘guiding of the solid’. Ultimately, with the term solid being conceptual thirteen and fifteen different responses were provided by students at the FB-II and Pruned-II Levels.



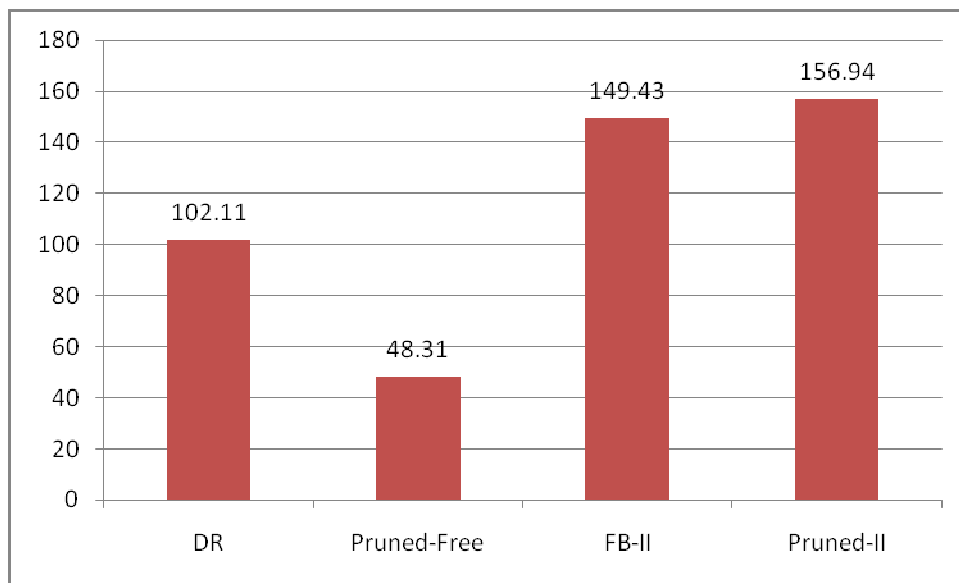
### 6.8.2 Average Time Taken To Identify a Product

In addition to identifying products based on their function structures, participants denoted the amount of time taken to identify each product. Figure 45 illustrates the average time taken by all participants for the rice cooker at each level of abstraction. Participants were able to identify a product the fastest at the Pruned-Free level, at approximately twenty seconds, and the slowest at the FB-II level, at approximately ninety-seven seconds or one minute and thirty-seven seconds. There was a time difference of approximately thirteen seconds between the DR and Pruned-Free abstractions, which is interesting to note considering the MUST – DR has seventeen functions incorporated into its function structure and the Pruned-Free model only has five. There is also an approximate thirteen-second time difference between the time taken to identify the rice cooker at the FB-II and Pruned-II level.



**Figure 45: Average time taken in seconds taken by refined user study participants to identify the Black & Decker rice cooker at four abstraction levels.**

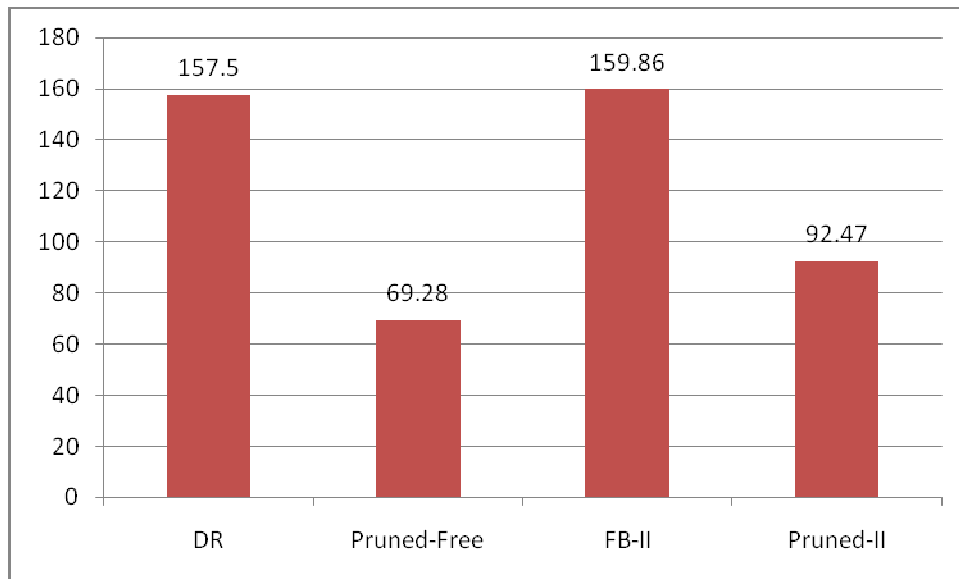
Figure 46 illustrates the average amount of time participants took to identify the four representations of the DeWalt Sander. Similar to the rice cooker participants were able to identify a product at the Pruned-Free level the fastest. However, unlike the rice cooker participants took the longest time identifying a product at the Pruned-II level; with an average time of 157 seconds. The time difference between the Pruned-Free level and DR for the sander is also much greater than with the rice cooker, at roughly 54 seconds. The average time taken at the FB-II and Pruned-II level were fairly close with only a 7.5 second time difference.



**Figure 46: Average time taken in seconds taken by refined user study participants to identify the DeWalt sander at four abstraction levels.**

Figure 47 shows the average time taken results for the Shopvac vacuum cleaner. Similar to the rice cooker and sander participants were able to identify a product the fastest from the four Shopvac representations at the Pruned-Free abstraction level, at 69.28 seconds. When comparing all four abstraction levels it is evident that the size of

the function structures was a primary factor in the amount of time taken by the participants. This is justified in the fact that participants took much more time trying to identify the Shopvac at the DR and FB-II abstraction levels than they did at the Pruned-Free and Pruned-II levels. Furthermore, the time difference between the DR and FB-II level is only 2.36 seconds. In addition, the time difference between the Pruned-Free level and Pruned-II is far less when comparing the Pruned-Free level to the remaining abstraction levels.



**Figure 47: Average time taken, in seconds, taken by refined user study participants to identify the Shopvac vacuum cleaner at four levels of abstraction.**

Figure 48 illustrates the average time taken by participants to identify a product from the four representations of the electric screwdriver. Similar to the other three products used in the study, the participants were able to identify a product at the Free Comp level the fastest and like the rice cooker participants took more time identifying a product at the FB-II level. The time difference between the DR and Free Comp level is

approximately 9 seconds and the 56 seconds between the FB-II level and Pruned-II. Overall participants took far less time to identify a product at the DR and Pruned-Free level compared to the FB-II and Pruned-II. This suggests that the specificity of terms within the models had a greater impact on the amount of time taken by participants as opposed to the size of the model.



**Figure 48: Average time taken, in seconds, taken by refined user study participants to identify the electric screwdriver at four levels of abstraction.**

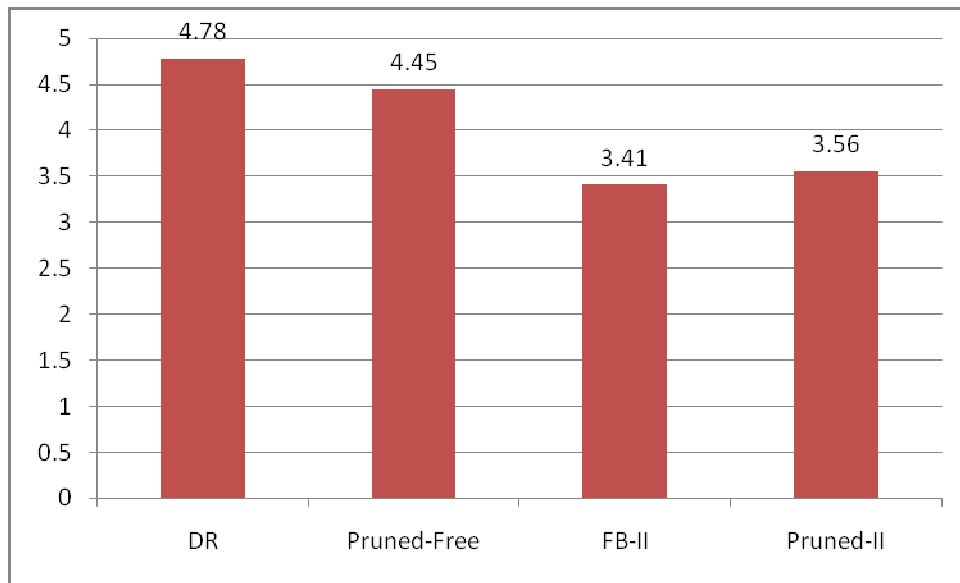
As a result of averaging the time taken by participants, it is evident that participants were able to identify products much faster when a product is modeled at the Pruned-Free level of abstraction. The results also assert that function structures modeled at the FB-II abstraction level take longer to interpret.

Overall the results suggest that the usage of free language reduces the time taken to identify a product from a function structure. Additionally, an increase in the number of functions within a functional model also increases the time to interpret the model. This is

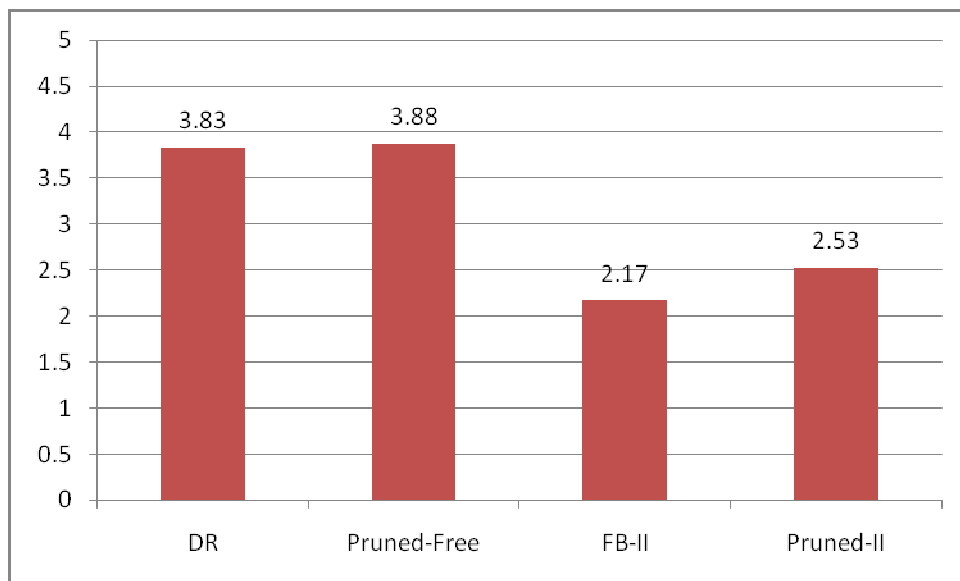
justified when analyzing the time taken to interpret the DR and Pruned-Free models, which is far less than the FB-II and Pruned-II models. The confidence level of each participant was also recorded in this study to gain further insight on towards the decisions of the participants, which is discussed in the next section.

### 6.8.3 Confidence Averages

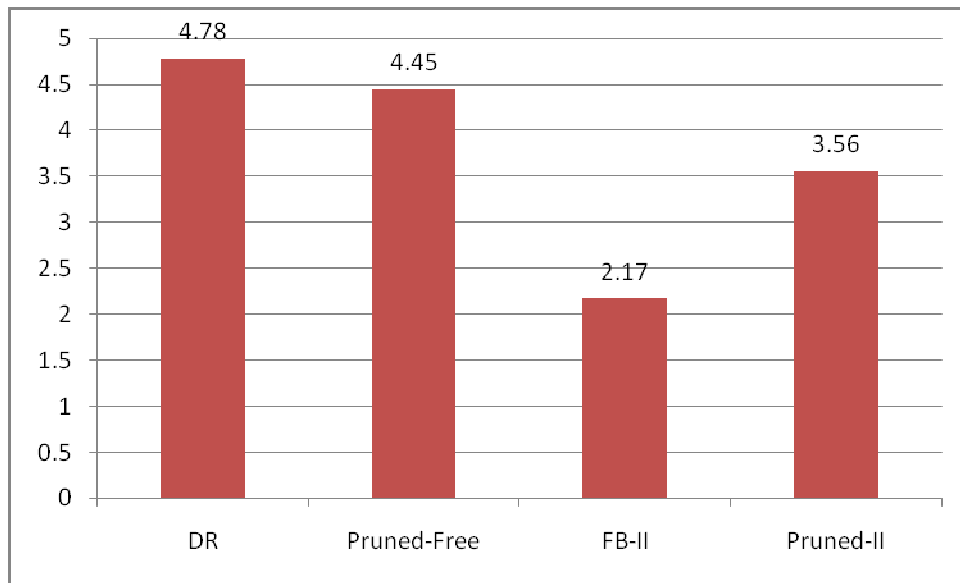
In addition to key indicators and response time, participants of the refined user study rated how confident they were in their function structure identifications. Participants rated their confidence on a scale from 1 to 5; 1 representing low confidence/not sure and 5 corresponding to highly/extremely confident. Figure 49, Figure 50, Figure 51, and Figure 52 illustrate the responses given by participants for the Black & Decker rice cooker, DeWalt sander, Shopvac vacuum cleaner, and electric screwdriver respectively. For the rice cooker, Figure 49, participants were the most confident with their responses for function structure modeled at the DR level, followed by the Pruned-Free, then Pruned-II and finally FB-II. Figure 50 illustrates the results of the sander, and participants were most confident in their responses at the Pruned-Free level, followed by the DR, then Pruned-II, and FB-II. As for the shopvac, Figure 51, the participant's confidence rating is similar to the rice cooker in terms of ranking the abstraction levels (DR, Pruned-Free, Pruned-II, and then FB-II). Participants were more confident identifying a product from the screwdriver's model at the Pruned-Free level, followed by the DR, Pruned-II, and then FB-II level.



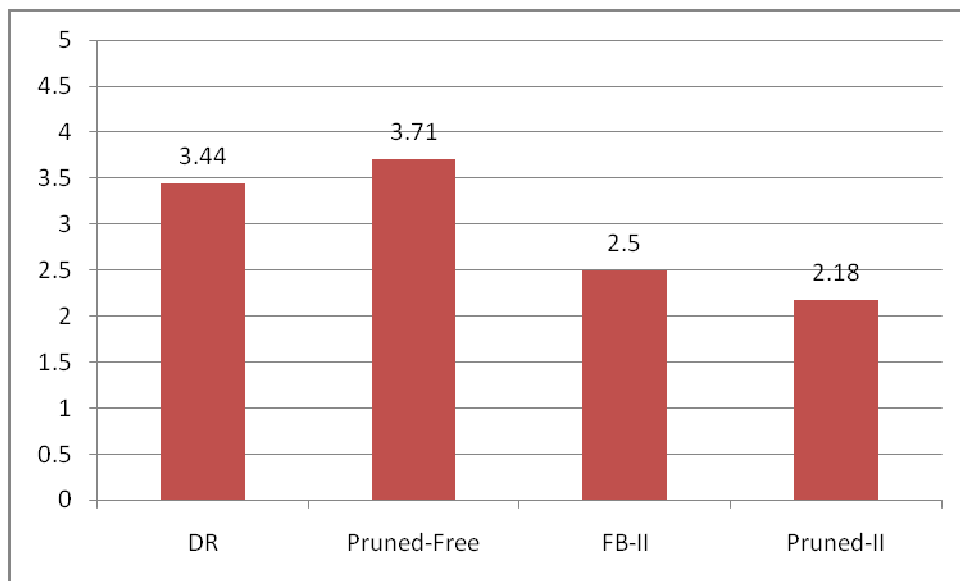
**Figure 49: Refined participants average response confidence rating for the Black & Decker rice cooker function structure at four levels of abstraction.**



**Figure 50: Refined user study participants average response confidence rating for the DeWalt Sander function structure at four levels of abstraction.**



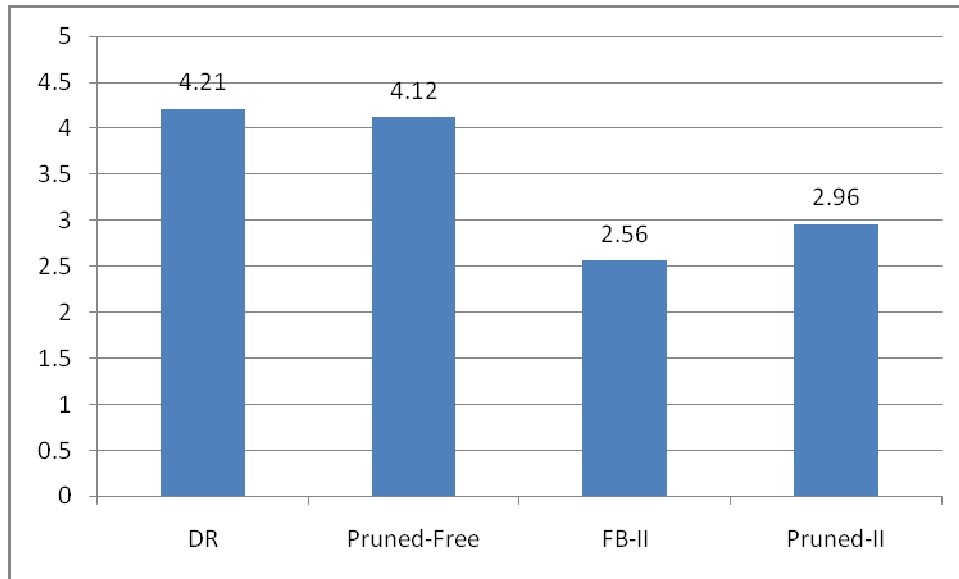
**Figure 51: Refined participants average response confidence rating for the Shopvac vacuum cleaner function structure at four levels of abstraction.**



**Figure 52: Refined participants average response confidence rating for the Electric Screwdriver function structure at four levels of abstraction.**

Figure 53, illustrates the overall average participant confidence for each abstraction level. These results suggest that the participants were more confident identifying products modeled at the DR and Pruned-Free level than they were with

products modeled at the FB-II and Pruned-II levels. Therefore, it is implied that the usage of free language terms boosted the confidence of the participants in their decision making. Furthermore, the numbers of functions has very little effect on the confidence of the respondents. However, further studies must be undertaken to determine what functions may have an effect on interpretability.



**Figure 53: Overall averages of participant confidence levels for each abstraction level based on all products analyzed.**

#### 6.9 Conclusions from Refined User Study

In this section, the results and observations from Section 6.7 and Section 6.8 are summarized. Four key conclusions are identified from the refined user study:

1. *The use of free language improves the human interpretability of function structures compared to controlled vocabularies.*
2. *Function structures with a higher number of functions take longer to interpret.*



3. *Function structures with the same number of functions, and with different flow specificity have vastly different interpretability*
4. *The confidence level of student response decreases when keywords are eliminated.*

## CHAPTER 7: INITIAL AND REFINED USER STUDY ANALYSIS

In this section the results from the DR, FB-II, and Pruned-II function structures from the initial and refined user study are analyzed. Table 14, outlines the percentage of exact/similar, functionally dissimilar, and no response replies given for the rice cooker during the initial and refined user study. At the DR level the results came out exactly same for both studies; all students identified the rice cooker exactly from this model. The percentages of exact/similar responses were slightly better during the initial user study at the FB-II and Pruned-II level. 81% of the participants identified exact/similar products during the initial study at the FB-II level, compared to 72% during the refined study. All participants identified exact/similar products at the Pruned-II level during the initial, this percentage dropped by slightly during the refined study, with 94% of the responses being exact/similar.

**Table 14: Response comparison between initial and refined user study: Black & Decker rice cooker.**

		Exact/ Similar	Dissimilar	No Reponse
MUST - DR	Initial	100%	0%	0%
	Refined	100%	0%	0%
Pruned-Free	Initial	N/A	N/A	N/A
	Refined	67%	0%	33%
FB-II	Initial	81%	6%	13%
	Refined	72%	17%	11%
Pruned-II	Initial	100%	0%	0%
	Refined	94%	6%	0%

Table 15 outlines the difference in responses for the DeWalt sander for the initial and refined user studies. The results show an approximate 9% difference in the number of exact/similar responses at the DR for the two studies; with students performing better slightly during the initial user study. Results from the FB-II level were the worse out of the three products at every abstraction level, with dissimilar and no responses making up 87% of the responses during the initial study and 94% during the refined study. The results are somewhat similar at the Pruned-II level with the dissimilar and no responses accounting for 88% of the responses during the initial and 83% from the refined study.

**Table 15: Response comparison between initial and refined user study: DeWalt sander.**

		Exact/ Similar	Dissimilar	No Reponse
MUST - DR	Initial	81%	0%	13%
	Refined	72%	28%	0%
Pruned-Free	Initial	N/A	N/A	N/A
	Refined	67%	28%	6%
FB-II	Initial	13%	81%	6%
	Refined	6%	61%	33%
Pruned-II	Initial	13%	44%	44%
	Refined	17%	72%	11%

The initial and refined user study results of the Shopvac are outlined in Table 16. The results of the MUST –DR are similar for both studies. However, at the FB-II and Pruned-II level the refined study participants did much better than the initial study

participants. At the FB-II abstraction level there is nearly a 20% increase in exact/similar responses and a 40% increase at the Pruned-II abstraction level.

**Table 16: Response comparison between initial and refined user study: Shopvac vacuum cleaner**

		Exact/ Similar	Dissimilar	No Response
MUST - DR	Initial	75%	25%	0%
	Refined	78%	22%	0%
Pruned-Free	Initial	N/A	N/A	N/A
	Refined	94%	6%	0%
FB-II	Initial	31%	56%	13%
	Refined	50%	28%	22%
Pruned-II	Initial	38%	13%	50%
	Refined	78%	17%	6%

**Table 17: Response comparison between initial and refined user study: Screwdriver**

		Exact/ Similar	Dissimilar	No Response
MUST - DR	Initial	N/A	N/A	N/A
	Refined	78%	17%	6%
Pruned-Free	Initial	N/A	N/A	N/A
	Refined	78%	17%	6%
FB-II	Initial	N/A	N/A	N/A
	Refined	0%	83%	17%
Pruned-Free	Initial	N/A	N/A	N/A
	Refined	6%	89%	6%

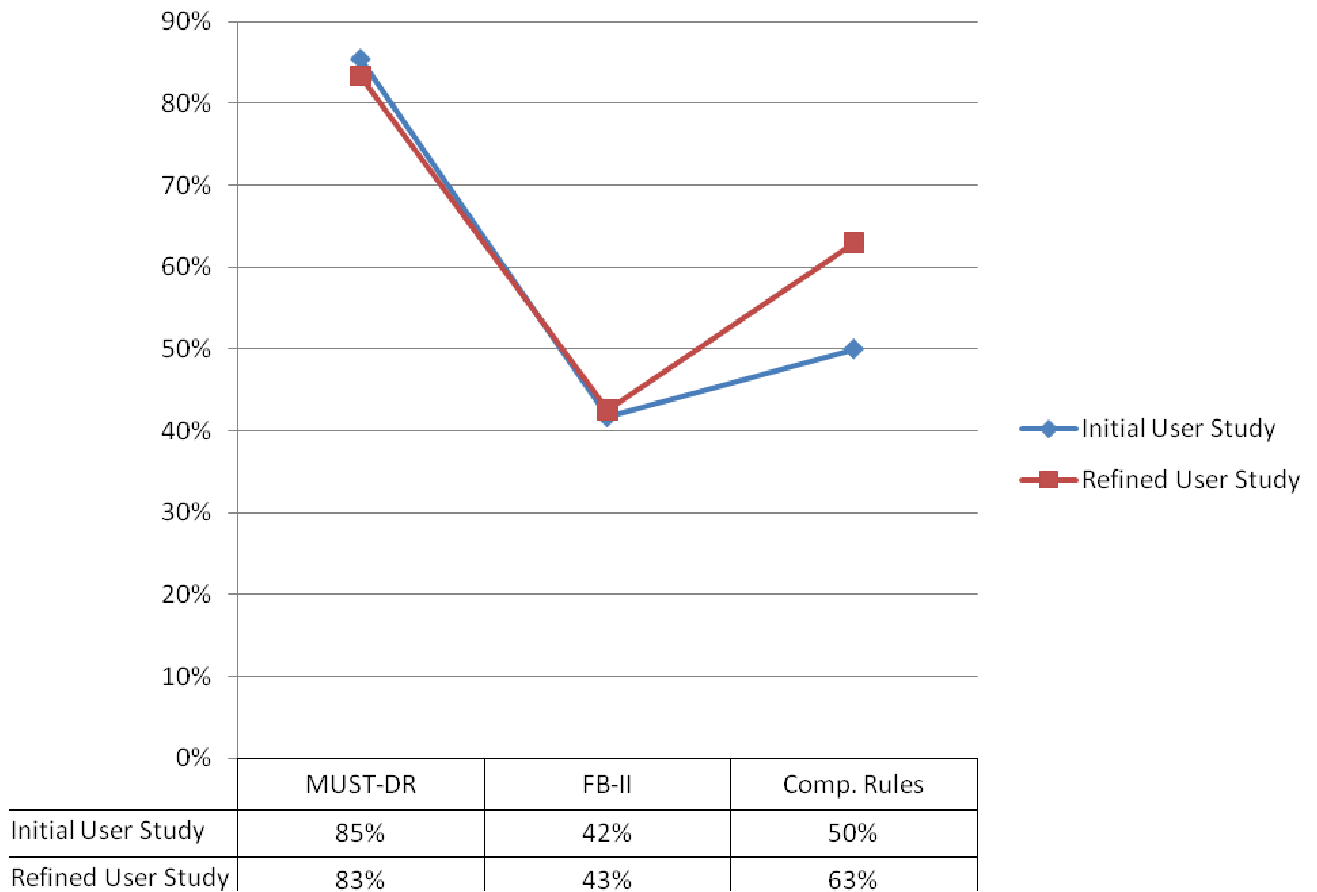
From the results it is evident that interpretability is strongly related to keywords in the function structure. Similar to the initial user study the main enabler that aided participants in identifying products from the function structures were keywords, which are non-Functional Basis terms borrowed from the natural English language. This key enabler invalidates a major claim of the Function Basis vocabulary, which states that the Functional Basis is adequate for describing functionality of products. However the use of non-Functional Basis terms in the DR and Pruned-Free abstraction level yielded higher levels interpretability than the function structures that did adhere to the functional basis. Table 18 outlines the average percentages of exact/similar responses for each abstraction level based on the responses given for the products modeled in the refined study. Function structures from the design repository (DR) were the easiest to interpret, followed by the Pruned-Free models, Pruned-II, and then the structures modeled at the FB-II level. Participants were also almost twice as confident in their decisions when analyzing function structures modeled at the DR and Pruned-Free level compared to FB-II and Pruned-II abstraction level.

**Table 18: Average exact/similar response percentages based on abstraction levels used in refined user study**

MUST - DR	82%
Pruned-Free	76%
FB-II	32%
Pruned-II	49%

Overall the trend in exact/similar responses for the initial and refined user study for the DR, FB-II, and Pruned-II abstraction level are roughly the same, with some

discrepancy coming from the Pruned-II level. The results averaging the rice cooker, sander, and shopvac's exact/similar percentages at the DR, FB-II, and Pruned-II abstraction levels are illustrated in Figure 54. From the DR to FB-II level the results overlap, however, there is a slight gap between the studies at the Pruned-II level. Despite the gap between the Pruned-II abstraction levels, both studies suggest that interpretability decreases from the DR to FB-II level but some interpretability is restored at the Pruned-II level.



**Figure 54: Comparison of overall exact/similar percentage of responses for each abstraction level from the initial and refined user study.**

In this section, the results and observations presented in Section 5.4 and Section 5.5 are critically interpreted and analyzed. From the results four key conclusions are made:

***1. The use of free language improves the human interpretability of function structures compared to controlled vocabularies.***

In regards to the first conclusion, the main enablers that helped the correct identification of products are the keywords, which are non-Functional Basis terms borrowed from the natural English dictionary. The use of such terms in the function structure within the Design Repository is, in fact, an aberration from the main purpose of the Functional Basis: consistency of product description. It also invalidates a major claim that the Functional Basis vocabulary is adequate for describing functionality of products, as the use of non-Functional Basis term in the DR and Pruned-II abstraction level yielded higher interpretability than the FB-II and Pruned-II levels. In fact, when the function structures were translated from the DR level to indeed adhere to the Functional Basis vocabulary (FB-II), the success rate of product identification drops significantly: approximately 40%. This suggests that the use of the Functional Basis controlled vocabulary does indeed reduce the interpretability of models.

***2. The representation of environmental context improves the human interpretability of function structures.***

The second claim is validated in this research from two different perspectives. First irrespective of the products, the inclusion of contextual information in the DR

abstraction level is shown to produce the highest interpretability of function structures, out of the three abstraction levels. Second, within a specific abstraction level (DR), a strong correlation between the density of contextual keywords and the interpretability of the models is shown. As explained in Section 5.5.2, the description of the environment within function structures contradicts the classical notion of function modeling, where solution-neutrality and abstract descriptions are believed to increase the usefulness of the models to designers. However, the current user study shows that the inclusion of such terms helps a more intuitive recognition of the models, thereby increasing their utility to designers. The higher the density of contextual keywords in the model, the easier it is for the designer to recognize the product, as the context provides additional information about the product to the designer.

***3. Abstraction of function structures generally reduces the uniqueness of the model, but promotes the description of the class of functionally similar products, rather than a specific one.***

This claim is in agreement with the classical notion of functional abstraction, and is supported in the user study. The number of exact identifications is observed to reduce with the increasing abstraction levels of function structures. For example, the number of exact identifications reduces from fourteen to eight to five, when the Black & Decker rice cooker model is translated between the DR, FB-II, and Pruned-II levels. By contrast, the number of identification of similar products generally increases between these levels. For example, in the case of the Black & Decker rice cooker, the numbers of similar identifications are two, five, and eleven in these three levels. Similarly, in the case of the



Dewalt Sander, these numbers are four, six, and six. Notably, the two steps of abstraction are realized by two different mechanisms. The first step, from the DR level to the FB-II level, is obtained by eliminating the contextual information from the function structures, while the second step, from the FB-II level to the Pruned-II level, is obtained by eliminating auxiliary functions from the FB-II version using the composition rules. However, based on the similarity of the above trends, it appears that both steps have similar end effects on the function structures so that the models become less specific, but represent a larger set of products that are functionally similar. For example, the coffee maker is identified as similar to the rice cooker, and the lawnmower is identified to be similar to the sander, for reasons explained in Section 5.2.

A significant exception to the increasing number of similar product with increasing abstraction, as discussed in the last paragraph, can be seen when the number of exact products are counted as similar products. This exception leads to a deeper understanding of the two abstraction mechanisms discussed in the introduction of Chapter 4, which is outlined in Conclusion #4.

***4. The two mechanisms of functional abstraction, namely elimination of context and elimination of auxiliary functions and flows are essentially different; despite the similarity of their end effects on function structures noticed in conclusion #3. They do not represent intensities of the same effect. Rather, they are two independent ways of achieving functional abstraction.***

The three levels of abstraction used in this research were hypothesized to be different magnitudes along the same dimension. However, if this one-dimensional model of the abstraction was to correct, and increasing abstraction was supposed to help the search of functionally similar products as explained in conclusion #3 the total number of exact and similar products identified by the participants is expected to grow from the DR level to the FB-II level and farther to the Pruned-II level. In this context, the exact product is counted as a similar product too. The results of the user study, however, contradict this expected trend. The total number of exact/similar products first reduces from the DR level to the FB-II level, then increases or remains the same, from the FB-II level to the Pruned-II level. Contrary to the expectation, the first translation reduces the interpretability of similar function structures despite the elimination of details. As discussed in conclusion #2 this reduction happens as a result of removing details pertaining to the specificity and context of the model, which actually helps in identifying the products. By contrast, in the second step, the identification of similar products improves, as the model becomes more interpretable when they are cleaned up from the auxiliary functions using the pruning rules from Section 3.3, allowing the designer to focus on the essential functions.

Conclusion #4 serves as the motivation to refine the user study and analyze a fourth abstraction, known as Pruned-Free which is characterized by the elimination of auxiliary functions, but retains the contextual flows. It is hypothesized that these abstraction levels will be easier to interpret compared to the DR, FB-II, and Pruned-II levels.

## CHAPTER 8: ANSWERS TO THE RESEARCH QUESTIONS AND OVERALL CONCLUSIONS

In this chapter, the results, observations, and conclusions drawn from the user experiments are related to the research questions proposed in Chapter 1. In Section 8.1, the research questions are revisited, followed by answers to these questions.

### 8.1 Research Questions

Function models have been proposed as a tool for representing product information during the conceptual design phase of the design process. Function structures are specific types of functional models that capture the decomposed functions of a product as well as the interconnectedness of the functions. In this research, the interpretability of function structures at different levels of abstraction has been evaluated to understand their usefulness to designers. The following research questions have been addressed in this research.

RQ1. What type of contextual information should be included within function structures to ensure human interpretability?

RQ2. Are there benefits of differing levels of function structure abstraction?

#### 8.1.1 Answer to RQ1

*In addition to the overall functionality of a designed product, free language and environmental interactions should be incorporated into its function structure to ensure interpretability.*

It was determined through the user studies that the use of context specific terms improves human interpretability of function structures compared to a controlled vocabulary. Notably, the main enablers that helped with exact/similar product identification of products were the keywords, which were non-Functional Basis terms borrowed from the natural English dictionary. The use of terms in the function structures within the Design Repository is in fact, an aberration from the main purpose of the Functional Basis: consistency of product description. It also invalidates a major claim that the Functional Basis vocabulary is adequate for describing functionality of products, as the use of the non-Functional Basis terms in the DR abstraction level abstraction level consistently yielded higher interpretability of function structures than the FB-II and Pruned II level.

The results of the user study also suggest that the representation of environmental context improves the human interpretability of functions. Irrespective of the products, the inclusion of contextual information in the DR abstraction level is shown to produce the highest interpretability of function structures, out of the four abstraction levels. The description of the environment within function structures contradicts the classical notion of function modeling, where solution neutrality and abstract descriptions are believed to increase the usefulness of the models to designers. However the user studies show that the inclusion of such terms helps a more intuitive recognition of the models, thereby increasing their utility to designers. The higher the density of contextual keywords in the model, the easier it is for the designer to recognize the product, as the context provides additional information about the product to the designer.

### 8.1.2 Answer to RQ2

*Yes, there is a benefit to differing levels of function structure abstraction. Function structure abstraction has the potential to promote the description of the class of functionally similar products, rather than a specific one.*

In this study, abstraction of function structures was achieved in two different ways: loss of specificity and context, and reduction of model size. The results of the study suggest that the benefit of function structure abstraction is that it has the potential to promote the description of the class of functionally similar products. Based on how abstraction is defined in this research, the Pruned –II representation would be considered the most abstract out of four abstraction levels analyzed in the study. However, products modeled at this abstraction level received the most functionally similar product responses from user study participants overall. This abstraction level could render useful to designers consider several researchers have asserted that functional model should enable designers to develop more creative and broad solutions through the use of functional similarity and analogy based design.

## 8.2 Research Opportunities

This thesis aids in the formalization of function structures; by analyzing the interpretability of function structures at various levels of abstraction. However, this thesis only scratches the surface at what type of information is, and should be contained in function structures. Therefore, revising the user study and validating other functional modeling research efforts with the results presented within this thesis would serve as

great research opportunities. These research opportunities are discussed in detail in Section 8.2.

### 8.2.1 Limitations of User Study

Considering all the benefits that functional modeling provides designers, knowing what type of information to incorporate in a function model to ensure clarity amongst designers, would be beneficial to design engineers. There is several research opportunities that should be addressed based on the conclusions of the user studies presented in this thesis. First, the user study should be completed again with a larger group of students and greater breadth of student experience, ranging from undergraduate students to graduate students. It would render beneficial if the study was automated in such a way that participants could visit a designated website and complete the user study at their leisure. This would provide the opportunity to collect more data in less time. More data would serve as a means to validate all claims of the initial and refined user studies. Second, a few more products should be investigated seeing that only four products were evaluated in this study. Finally, the functions should be augmented within the function structures. For instance, within this study all function terms (such as rotate, store, and convert) used in the study were secondary terms from the Function Basis, so these terms should be augmented. Augmenting these terms could ultimately provide support towards extending and augmenting the Functional Basis.

### 8.2.2 Information Metric

Based on information theory, which was originally developed in the context of communication, researchers from Clemson University have proposed an information metric for computing the information content of function models [14]. Based on the metric, information content is computed by analyzing the number of functions and flows within a given model. The metric is only applicable to a function model that was developed by choosing functions and flows from a finite vocabulary. However, the metric has yet to be externally validated to reflect the opinions of designers about the practical value of function models and vocabularies. Therefore, data from FB-II and Pruned-II function structure abstraction levels used in this research could serve as a means to validate the information content metric and its usefulness; considering the functions and flows from both of these abstraction levels were developed from a finite vocabulary.

### 8.3 Concluding Remarks

The objective of this research is to investigate the human interpretability of function structures that adhere to claims made in functional modeling research. One being the classical notation that function models being solution neutral and having abstract descriptions increase the usefulness of the model to the designer. However, this research shows that the description of the environment within a model increases human interpretability. This also refutes the claim made by the developers of the function structure-pruning rules who believed removing auxiliary functions from a function structure are more beneficial to designers.

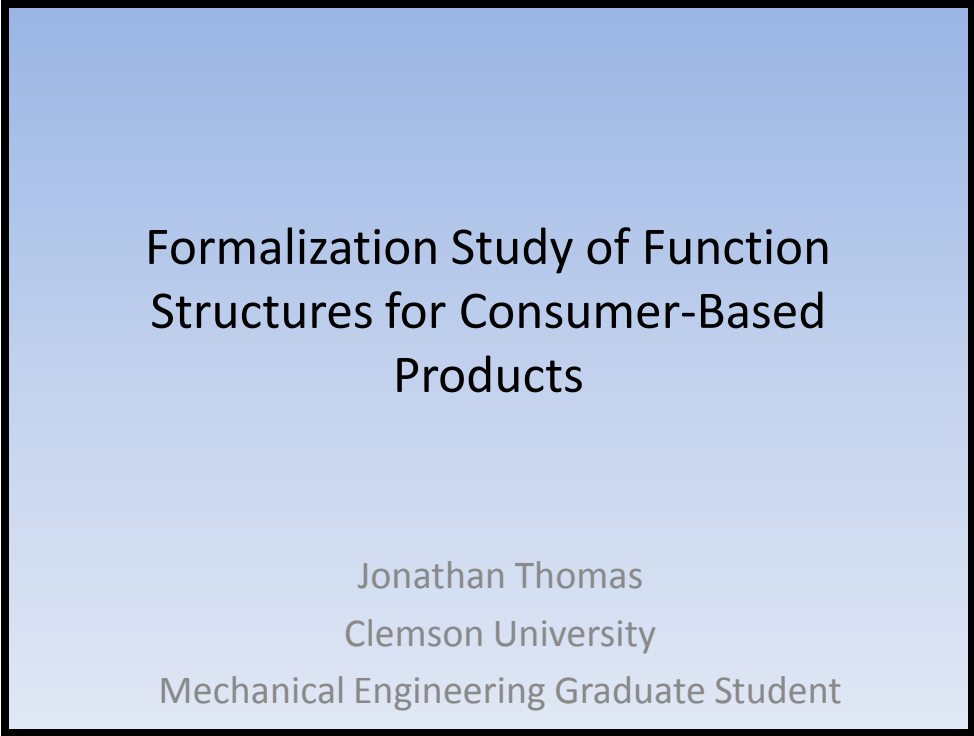
The adequacy of the Function Basis is also in question, based on the results presented in this thesis. The conclusion in this thesis shows that the usage of free language in function structures increases the context of the function structure but violates the intent of the Functional Basis. Thus, the Functional Basis must be expanded or an additional representation scheme must be developed to capture context-specific information of a product to ensure human interpretability. Most likely the Functional Basis should not be expanded but rather two models of a product should be developed that include the function structure and a formal context model. These two models should be then integrated, thus allowing the function and the context to be explicitly modeled and queried independently as well as jointly.



## APPENDICES

## APPENDIX A: PRESENTATION SLIDES

The following images are the slides presented to the participants for training and normalization, as discussed in Sections 5.1.2 and 6.2



# Formalization Study of Function Structures for Consumer-Based Products

Jonathan Thomas  
Clemson University  
Mechanical Engineering Graduate Student

# INTRODUCTION TO FUNCTIONAL MODELING & FUNCTION STRUCTURES

## Introduction To Functional Modeling

- Function: “intended input/output relationship of a system whose purpose is to perform a task” (Pahl & Beitz)
- “A function of a product is a statement of a clear, reproducible relationship between the available input and the desired output of a product, independent of any particular form.” (Otto & Wood)
- Functional modeling provides an abstract, yet direct method for understanding and representing an overall product function without the use of physical structures.

## Benefits of Functional Modeling

- Functional modeling enhances the characteristics of a creative designer, by providing a systematic approach for decomposing a product design problem into simpler sub problems.
- Greater breadth of concepts may be generated in product design using functional modeling.
- Allocating design team resources is aided by functional modeling.
- Product architecture decision may be made earlier in the development process through functional modeling.
- Function models provide a basic systems approach to design, as needed for supporting experimental analysis methods.
- Functions represent what parts of the product do in a form independent way; constraints are intrinsic properties of the entire product.

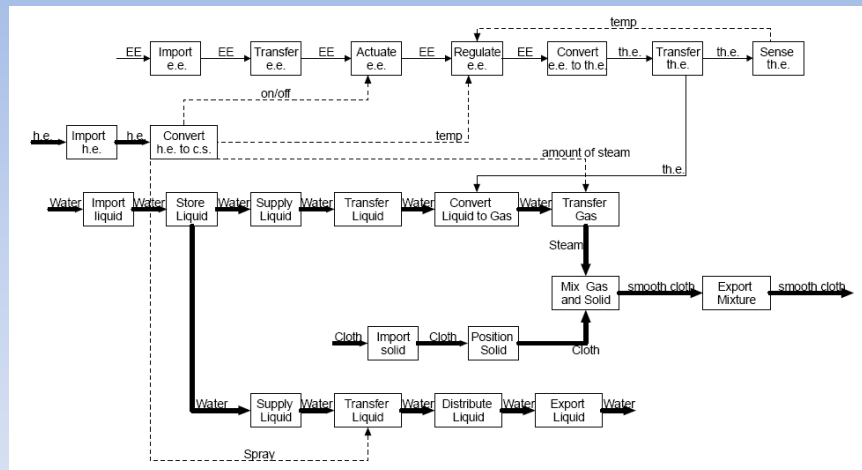
-Otto & Wood

## Function Structures

- Combination of meaningful and compatible sub-functions into an overall function
- Sub-functions are expressed in active verb-noun pairs (ex. "increase pressure", "transfer torque", "reduce speed", etc.)
- Statements are derived from the conversions of energy, material, and signal.
- Energy: mechanical, thermal, electrical, chemical, optical, nuclear, pneumatic, etc.
- Material: gas, liquid, solid, plasma, mixture, human, etc.
- Signals: control status, magnitude, display, control impulse, data, information, etc.

## FUNCTION STRUCTURE EXAMPLE

### Electric Iron



\*Inputs: Human Energy(HE), Electrical Energy (EE), Cloth, and Water

\*Outputs: Smooth Cloth and Water

QUESTIONS?

EXPERIMENTAL PROTOCOL

## Protocol

- You will be given a packet, containing pictures of 48 consumer products to review. (Five minutes)
- You will be given nine function structures (Three at a time)
- You have ten minutes to identify each product, within the function structure
- Denote what aspects of the structure aided you in your decision.
- Denote the amount of time taken to identify each product.
- Write the last four-digits of your student ID in the top left hand corner.

QUESTIONS?

## APPENDIX B: INITIAL USER STUDY DATA

**Table B.1: Black & Decker Rice Cooker results (DR)**

Student	Product	Time (min)	Notes
3005	Rice Cooker (G4)	3:30	Transfer of thermal energy to the mixture of solid and liquid and output being rice
3846	Rice Cooker	4:13	Inputs rice and water. Output:rice.
8271	Rice Cooker	9:35	Blank
5869	Rice Cooker (G4)	2:47	Bowl to store rice, EE-Th.E (electricity to heat) Export Solid-separate rice from bowl
4629	G4- Rice Cooker	BLANK	Bowl , Rice and Water Input. "Why its so obvious, I love rice"
3341	G4 (Rice Cooker)	BLANK	Rice and bowl being imported and exported
299	Microwave (A2)	6:52	Transferring the thermal energy to the solid+liquid mixture sealed it
2438	G1 (Wok)	:45	Very specific inputs/outputs. Also, regulations and transfer of thermal energy wer good clues
1804	G4 (Rice Cooker)	:10	Rice, Water, EE, HE inputs
6512	Rice Cooker (G4)	2:00	Thought G4 was a crock pot but nothing else fits unless there is a bowl of rice in the microwave



64	Rice Cooker (G4)	1:45	So I guess G4 is a rice cooker even though previously I thought it was a crock pot/ It's the only thing I see that could use rice.
3770	Electric Cooker (G4)	2:05	EE, Bowl, Rice
959	Rice Cooker	1:00	Rice + Water + HE
1423	G4 (Rice Cooker)	:30	BLANK
8080	G4 (Rice Cooker)	1:11	rice, water, and bowl and conversion of EE to Th.E
4514	G4 (Electric Cooker)	:20	From the components (both input and output) I can directly identify the product.

**Table B.2: Black & Decker Rice Cooker Results (FB-II)**

Student	Product	Time (min)	Notes
3005	G4 (Electric Cooker)	9:14 (total packet time))	Transfer of thermal energy to the mixture of solid and liquid and output being rice
3846	G4 (Rice Cooker)	Blank	Solid and Liquid inputs and outputs
5869	Blank	Blank	Blank
4629	Rice Cooker	Blank	Solid & Liquid inputs being mixed. Flow of EE & HE is relatively useless
3341	G4 (Rice Cooker)	BLANK	"Input includes both solid and liquid and export contains only solid." " EE will be transferred to Th.E"
299	Coffee Maker (E1)	blank	mix Solid + liquid - Coffee beans + water. Position + Store Solid - Coffee Mug

2438	Coffee Maker (E1)	2:45	store Solid & liquid and mix solid & liquid and transfer thermal energy
1804	Rice Cooker	blank	End Result is solid-Rice. Requires liquid which is water. Electricity energy to boil rice. Human energy to switch to EE
6512	Coffee Maker (E1)	4:00	Export Mixture; Position solid; convert EE to Th. E
64	Coffee Maker (E1)	1:45	First thought juicer, then I saw the heating aspect
3770	Electric Cooker	BLANK	BLANK
959	Coffee Maker (E1)	BLANK	Transfer Th. E. two different solids as input (sugar & coffee powder) adding liquid (milk or water).
1423	Engine (d4)	4:00	Transfer Th. E.
8271	Rice Cooker (G\$)	2:00	Mix Solid & Liquid
8080	BLANK	BLANK	BLANK
4514	G4 Pressure Cooker	BLANK	From the inputs and outputs I can see it helps to cook food. It should be a pressure cooker

**Table B.3: Black & Decker Rice Cooker Results (Pruned-II)**

Student	Product	Time	Notes
3005	Electric Cooker (G4)	2:03	Th. E conversion from EE. That being imparted to solid liquid mixture and the output being solid liquid mixture
3846	Coffee Maker	BLANK	Inputs & Outputs. EE being converted to Th.E
8271	Coffee Maker	2:00	Blank

5869	Coffee Maker	3:02	Store Solid in form of powder cubes(sugar), store liquid in form of milk/water. Coffee solid-liquid mixture
4629	E1 (Coffee Maker)	BLANK	Solid and Liquid Being Mixed
3341	E1 (Coffee Maker)	Blank	Convert Ee to Th. E. Solid-Liquid Mixture export. Store both solid & liquid
299	Crock Pot (G4)	2:20	Mix Solid + Liquid - combining stuff to make stuff
2438	G4 (Crock Pot)	:30	Store of solid & liquid. Th. E applied to mixture. Output is a mixture
1804	G1 (Wok)	BLANK	Output: Solid liquid mixture. Solid- Food. Liquid-water.
6512	Crock Pot Steamer (G4)	3:00	Inputing liquid & solid and creating Mixture
64	Crock Pot (G4)	0:45	This is the only product that exports only a solid-liquid mixture and it is heated
3770	Coffee Mixing Machine	BLANK	Convert EE to Th. E and solid/liquid mixture
959	Coffee maker	3:00	Solid+Liquid (coffee powder +water). Heat for Th. E. output coffee
1423	E1 (Coffee Maker)	1:19	Mix Solid & Liquid. Solid/Liquid Mixture output
8080	Coffee Maker (E1)	BLANK	Coffee maker stores both coffee grains and liquid(water) and mixes them by electricial energy.

4514	E1 (Coffee Maker)	1:20	I can see that solid is coffee powder, liquid is milk/water. HE is the amount of Liquid/solid to pour (It's a control signal).
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**Table B.4: Dewalt Sander Results (DR)**

Student	Product	Time (min)	Notes
3005	BLANK	BLANK	BLANK
3846	Sander (C2)	BLANK	Inputs: sand paper, wood, hand. Output: Wood
8271	Sander (C2)	5:00	BLANK
5869	BLANK	BLANK	BLANK
4629	I4 (Bench Grinder)	BLANK	Debris and Pn. E Output. Sandpaper.
3341	C2 (Sander)	BLANK	Import/ Export of Wood. Sand Paper
299	Sander (C2)	1:15	The imports actually helped more than functions. Wood, SandPaper, Wood, Debris, Pn.E
2438	C2 (Sander)	:40	Very specific inputs & outputs wood & sandpaper.
1804	?	BLANK	BLANK
6512	Sander (C2)	1:00	Sand paper, Guide solid, wood
64	Sander (C2)	1:00	Only one product uses sand paper. The use of wood helped too.
3770	Sander (C2)	BLANK	Sand Paper and wood.
959	Wood Cutter	3:00	Cutter for separating wood. Sand paper for sharpening cutting. Debris for wood chips.

1423	Sander (C2)	3:59	Separate Solid, Sandpaper, Debris/Pn. E Output
8080	Grinder (I4)	BLANK	Sandpaper. Energy conversion EE-ME
4514	I4 Wood Cutter	2:30	From the input and outputs

**Table B.5: Dewalt Sander Results (FB-II)**

Student	Product	Time (min)	Notes
3005	Vacuum Cleaner	:32	Output being solid. Conversion of ME to Pn.E
3846	Fork Lift	Blank	Human, HE, and Gas Input
8271	Nerf Gun	7:30	BLANK
5869	Toaster	Blank	Solid-to be cooked. Position Solid - Keep in place. EE to ME to ME & Pn. E
4629	F4 (Vacuum)	Blank	Solid Input and export and Sparation of solid.
3341	B4 (Hand Vac)	Blank	Human import, gas import, Both Solid imports, Transfer ME, human and solid export
299	Fork Lift (F3)	2:14	The humans interaction w/ the solid. Securing + guiding solid were important.
2438	B4 (Hand vac)	4:00	Sounds like other vacuum cleaners, wet/dry vac. Inputs: solid, gas, human. Outputs: solid, gas, human.
1804	Air blower (H4)	5:00	HE, Gas, Separate solid
6512	Nail Gun (D1)	1:00	Solid in, solid out with positioning. Human Input and guiding solid

64	Fork Lift (F3)	Blank	Position Solid, Guid Solid, Pneumatic Energy, Secure Solid
3770	Machine Gun (K3)	3:50	Export solid (bullet), export Solid Pn. E (pressure with which the solid is exported)
959	Lawn Mower	6:00	Separate solid, store solid particles.
1423	C4 Lawn Mower	4:20	Convert ME to Pn. E. Guide solid
8080	Fork Lift (F3)	1:00	BLANK
4514	Blank	4:00	Not clearly able to classify even after spending 4minutes.

**Table B.6: Dewalt Sander Results (Pruned-II)**

Student	Product	Time (min)	Notes
3005	vacuum Cleaner (f4)	9:14 (total packet)	Conversion of ME to Pn. E and storing solid
3846	BLANK	BLANK	BLANK
5869	BLANK	BLANK	BLANK
4629	Sander (C2)	BLANK	"The material flow makes it easy to identify what it is. The key words also include separate and Pn.E"
3341	F4 (Vacuum)	Blank	Convert ME to Pn. E. Store solid
299	Vacuum Cleaner (B2) ??	BLANK	Converting ME1 to ME2 - The extra step to separate and store the solid
2438	vacuum Cleaner (f4)	3:45	"Store solid" helps eliminate lots of options. "Pn. Energy" is a suction force.

1804	BLANK	BLANK	BLANK
6512	Lawnmower (C4)	3:00	Store Solid, Pn. E, Separate Solid, Convert HE to CS
64	Shop Vacuum (I1)	2:00	Pn. Energy separate and collecting solid
3770	BLANK	BLANK	BLANK
959	BLANK	BLANK	BLANK
1423	BLANK	BLANK	BLANK
8271	Fork Lift (F3)	2:30	Separate Solid. Store Solid
8080	BLANK	BLANK	BLANK
4514	Sewing Machine	BLANK	Human controls are used. Circled: EE, HE, and Pn. E.

**Table B.7: Shopvac Vacuum Results (DR)**

Student	Product	Time (min)	Notes
3005	Compressor (L4)	9:14(total packet)	Output is pneumatic energy and air
3846	Iron	blank	Thermal energy and Hand
5869	Rifle	Blank	Separate Solid, Debris, Store Solid
4629	G1 (Wok)	Blank	Hand input and flows
3341	D4 (Engine)	Blank	Blank
299	Vacuum Cleaner (F4)	BLANK	Guide Solid
2438	I1 (Wet/Dry vac)	3:00	Function FS-H had a "spinning brush" this one does not, yet still requires "Pn.E.
1804	Vacuum Cleaner (F4)	BLANK	Debris/Air, hand, human force, EE, Air, Inputs
6512	H4 (Leaf Blower)	3:00	Debris, Air, HF, Air,

64	C4 (Mower)	2:45	I only see two things that run on gas (except maybe the compressor if it is portable0 and the lawn mower is the only one concerned w/ debris + stores solid
3770	Compressor(L4)	BLANK	BLANK
959	Lawn mower	BLANK	BLANK
1423	Air Compressor (L4)	2:00	Convert ME to Pneumatic E. Import gas.
8271	I1 (Shop Vac)	5:00	BLANK
8080	Vacuum cleaner	BLANK	Debris/Air, Guid solid-gas mixture, store solid, export solid, convert ME to Pn. E, Guide gas, export gas.
4514	H4 (Air Blower)	BLANK	From the input as debris and air, and outputs as pneumatic energy I can identify it as air blower. As there is a human force input included.

**Table B.8: Shopvac Vacuum Results (FB-II)**

Student	Product	Time (min)	Notes
3005	Air Compressor (L4)	:37	Output being Pn. Energy and gas
3846	BLANK	BLANK	BLANK
8271	Vacuum (F4)	3:40	BLANK
5869	Bench Grinder (I4)	BLANK	Gas, Acoustic Energy, Pn. E



4629	L4 (Air compressor)	BLANK	Importing and Exporting Solid and Gas. "Really hard to identity"
3341	F3 (Fork Lift)	BLANK	Import Gas, Guide Gas, Acoustic Energy, Weight, Transfer Energy
299	Pan (G1)	4:18	Guide + Export Solid. Separate Solid From Gas, Guide Solid, Export Solid, Weight.
2438	C4 (Lawn Mower)	5:00	"Guide Solid" is kinda confusing, actually makes sense w/ lawn mower
1804	F3 Fork Lift	BLANK	BLANK
6512	Toaster (I2)	2:00	Acoustic Energy made me think instrument but I couldn't follow the function for guitar. Seemed like a toaster
64	Engine (D4)	1:38	"Becase of the gas aspect this has to be the fork lift of the engine and fork lift runs on pure gas I believe"
3770	Engine (D4)	BLANK	Th. E, Gas
959	Proclainer (skid steer)???	3:00	Lifting Weight
1423	Vacuum (F4)	3:19	On/Off, Acoustic Energy
8080	K1 (FAN)	BLANK	BLANK
4514	BLANK	BLANK	Unable to decide/identify

**Table B.9: Shopvac Vacuum Results (Pruned –II)**

Student	Product	Time (min)	Notes
3005	BLANK	BLANK	BLANK
3846	BLANK	BLANK	BLANK
8271	Microwave	1:39	BLANK
5869	BLANK	BLANK	BLANK

4629	F2 (Flashlight)	Blank	"The material flow makes sense"
3341	? (Can't read)	BLANK	EE import, gas and solid export
299	Lawn Mower	5:24	"Separating + Guiding solid determines grass flow"
2438	BLANK	4:00	No human interaction. Inputs/Outputs aren't specific
1804	L4 (Air compressor)	2:00	Pn. E., Solid, Gas
6512	-	5:00	No human input - all my guess require human input
64	-	5:00	Runs on EE & Gas? Exports a solid & Pn. E + th. E?
3770	Vacuum Cleaner	4:00	BLANK
959	Vacuum Cleaner	1:40	Solid + gas mixture. Separate solid from gas.
1423	Hand Vac. (B4)	5:10	BLANK
8080	F4 (Vacuum)	2:00	Gas solid mixture
4514	Blank	5:00	I have no clue

## APPENDIX C: REFINED USER STUDY DATA

**Table C.1: Rice Cooker Results (DR)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	Rice Cooker	G4	26	5	Rice. Thermal energy is used. Water is used.
1378	Cooker	G4	14	5	Rice as output
8193	Rice Cooker	G4	62	5	Rice. Mix Solid/Liquid.
2879	Electric Cooker	G4	60	4	Use of rice and water was input. Needs heat and electricity. Gives bowl and rice as output.
3631	Rice Cooker	G4	15	5	Rice, water on input side.
0580	Rice Cooker	G4	20	5	1) Ee to Th. E. 2) Rice, bowl. 3) Input of heat energy
1956	Rice Cooker	G4	105	4	Rice, heat energy, and water
4258	Rice Cooker	G4	72	4	Rice
8838	Rice Cooker	G4	30	5	Rice and bowl.
9311	Rice Cooker	G4	72	4	Rice/Bowl
9157	Rice Cooker	G4	6	5	Rice and water as input. Mixing in a bowl
8499	Rice Cooker	G4	25	5	Rice is cooked
1573	Rice Cooker	G4	10	5	Rice, bowl, water, Th. E.

3622	Rice Cooker	G4	27	5	1) Rice output/ input. 2) EE to Th. E
6251	Rice Cooker	G4	35	5	The use of "rice
3904	Rice Cooker	G4	9	5	Rice, bowl, solid liquid in.
7731	Rice Cooker	G4	10	5	Rice, bowl, water. Export mixture.
0261	Rice Cooker	G4	32	5	The input and output clearly states that rice and water are used.

**Table C.2: Rice Cooker Results (Pruned – Free)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	Rice Cooker	G4	40	4	Rice and water
1378	Cooker	G4	11	5	Output rice
8193	Rice Cooker	G4	39	5	"Rice" "Bowl" heats water.
2879	Electric Cooker	G4	16	5	Uses rice and bowl and water as input. Rice and bowl are output. Uses electricity and heat as input.
3631	Rice Cooker	G4	16	5	Rice and bowl on input side.
0580	Rice Cooker	G4	21	5	1) Input of rice and water. 2) Store solid and liquid. 3) Mix solid and liquid. 4) Use of TH. E (convert EE to TH. E)

1956	Rice Cooker	G4	32	5	Rice. Water. There is little abstraction the problem itself has little abstraction
4258	Crock Pot	G4	0	1	Rice
8838	Rice Cooker	G4	20	5	Rice + Water. Thermal Energy
9311	Rice Cooker	G4	15	5	Rice/bowl
9157	-	-	0	-	BLANK
8499	-	-	0	-	BLANK
1573	Rice Cooker	G4	10	5	Rice In
3622	-	-	0	-	BLANK
6251	Rice Cooker	G4	20	4	BLANK
3904	-	-	0	-	BLANK
7731	-	-	0	-	BLANK
0261	-	-	0	-	BLANK

**Table C.3: Rice Cooker Results (FB-II)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	Coffee Maker	E1	190	3	Solid is positioned: coffee is poured in filter
1378	-	-	0	-	BLANK
8193	Coffee Maker	E1	53	3	Not much. 2 solid in, 1 liquid in. Mixture/solid

					out
2879	Electric cooker	G4	78	4	Uses heat and solid/liquid as main input. Given solid is output. Uses electricity
3631	Candy M/C	L4	117	3	Mixing solid + liquid. (Coffee powder + water). Human energy
0580	Coffee Maker	E1	47	5	1) Input of EE, HE, Solid, Liquid. 2) Mixing solid and liquid. 3) output of mixture
1956	Washing Machine	D4	122	5	The overall structure. The input and output. The mixture of solid and liquid
4258	Coffee Pot	E1	108	3	Mix solid/ liquid
8838	Wok	G1	131	2	Use TH. E as input to mix solid and liquid. Export both a solid and a solid liquid mixture
9311	-	#REF!	137	2	Mix solid and liquid. Output solid
9157	Microwave Oven	A2	132	3	Import solid, storing and mixing with liquid to get a solid output using EE and HE
8499	Rice Cooker	G4	62	5	Import EE, HE, Solid and liquid. Output is solid
1573	Rice Cooker	G4	30	4	Impiort solid/ liquid separate output mixture as solid
3622	Pan	G1	75	5	1) Several solid input. 2) Liquid input. 3) Th.

					E convert 4) Export mixtture
6251	Popcorn Popper	J7	200	1	Imprt of solid and liquid: mixed with added heat. 2 solid flows were confusing
3904	Rice Cooker	G4	86	3	Import solid, liquid, heat
7731	Coffee Maker	E1	68	4	Solid, liquid, mixture export. H. E. to C.S. conversion. Export solid
0261	Electric Rice Cooker	G4	84	3	Only in rice cooker both solid(rice) and liquid (water) is added first. The output is also solid. Heat is needed to cook rice.

**Table C.4: Rice Cooker Results (Pruned –II)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	<i>Coffee Maker</i>	<i>E1</i>	57	3	Only one machine mixed solid. Heat applied. Solid is grounds, understood as coffee.
1378	<i>Coffee maker</i>	<i>E1</i>	71	2	Solid liquid mixture
8193	<i>Coffee Maker</i>	<i>E1</i>	38	2	EE to Th.E. Store/Mix. Liquid/solid. Made less confident because thermal energy is not shown added to the liquid as expected. Also don't expect solid/liquid mixture leaving
2879	Electric Cooker	G4	234	3	It converts electricity into heat/thermal energy. It takes solid and liquid as input. (What

					those inputs are depends on what you are cooking. Those can be from stove.)
3631	Electric Cooker	G4	104	4	Solid plus liquid mixture. Control signal
0580	Rice Cooker	G4	107	3	1)Store solid and store liquid. 2)Conversion of EE to Th.E. 3)Mix solid and liquid. 4)Solid liquid mixture.
1956	<i>Coffee Maker</i>	<i>E1</i>	90	4	Store liquid. Store solid. Mix solid & liquid
4258	<i>Coffee Pot</i>	<i>E1</i>	140	4	Store solid/liquid. Separate then mix.
8838	<i>Coffee Maker</i>	<i>E1</i>	71	4	Mix solid & liquid. Convert EE to TH. E.
9311	Coffee Maker	E1	36	4	Input solid. Output solid liquid mixture. Store solid, store liquid
9157	Coffee Maker	E1	45	5	Solid and input as input. Getting a solid and liquid mixture output
8499	Coffee Maker	E1	60	3	Solid and input as input. Getting a solid and liquid mixture output
1573	Rice Cooker	G4	30	5	Solid liquid separate in. Solid liquid mixture out. (could be coffee maker)
3622	Coffee Maker	E1	55	5	1) Store solid/liquid. 2) Solid-liquid mixture output
6251	Coffee Maker	E1	94	3	Mixing of solid and gas
3904	Coffee Maker	E1	121	4	EE to TH. E. Solid liquid mixture
7731	Juicer	H3	89	3	Solid and liquid mixture. HE as CS
0261	Wok	G1	81	3	Solid and liquid is needed to cook. EE to TH. E heats the stove. This happens to give



					cooked food
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**Table C.5: Sander Results (DR)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	Sander	C2	85	4	Sander paper is used. Wood is involved.
1378	Circular saw	F1	39	3	Output wood. Hand movements
8193	Sander	C2	128	5	"Hand" used to manipulate solid. "wood" and "sandpaper" gave it away.
2879	Sander	C2	45	5	It uses sand paper. It needs fuel (gas). Uses electricity
3631	Dewalt Grinder	C2	112	3	Sand, wood, sandpaper. "Possibly grinder
0580	Sander	C2	205	4	1) Words like wood, sand paper. 2) Hand guided. 3) Conversion of EE to ME
1956	Sander	C2	120	4	Sand paper. Wood Debris.
4258	Sander	C2	76	4	Sandpaper
8838	Sander	C2	130	4	Sand paper and wood
9311	Pencil Sharpener	J3	180	3	Input EE/Hand. Output wood
9157	Bandsaw	J1	89	3	Processing wood and seperating debris. EE input, guidng with hand. Using Pn. E to separate debris
8499	Vacuum Cleaner	F4	59	4	Pneumatic removal of debris and sand

1573	Sander	C2	17	5	Sandpaper. Wood
3622	Circular Saw	F1	87	5	1) Wood, debris output. 2) Sand paper
6251	Sander	C2	67	4	Use of the word "sandpaper" and there is only one possible sanding device
3904	Bandsaw	J1	95	3	Wood, debris
7731	Bench Grinder	I4	260	3	Eliminated all other options. Process soild. Use sand paper
0261	Sander	C2	44	3	Solid is imported by hand. ME is used to finish wood. Wood polished output.

**Table C.6: Sander Results (Pruned Free)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	Electric Sander	C2	72	4	Sand paper is used. Solid is separated. debris is?
1378	Circular Saw	F1	28	2	Output is debris and wood
8193	Sander	C2	34	5	"Sand paper" "wood" HE manipulates
2879	Sander	C2	28	4	Uses sander as one of the inputs. Works on wood. Debris is one of the outputs.
3631	Dewalt Sander	C2	57	3	* Sand paper
0580	Sander	C2	36	3	1) Input of HE & EE. 2) use of sand paper. 3) Output of wood and debris
1956	Sander	C2	34	5	Sandpaper, wood, debris
4258	Sander	C2	33	4	Sand paper

8838	Sander	C2	58	4	Sandpaper and wood. Note: Does the input have to be wood? Can it be drywall/plastic, etc.
9311	Band Saw	J1	24	4	Input output wood. Separate solid
9157	Band Saw	J1	148	4	Using ME to process wood and clearing the debris
8499	Wood Cutter	F1	46	4	Motor rotates with EE and cuts wood
1573	Sander	C2	25	5	Sandpaper. Wood
3622	Wood Cutter	F1	28	5	1) Wood debris output
6251	Sander	C2	0	4	"Sand paper"
3904	Sander	C2	80	4	Sand, wood, debris
7731	-	-	0	-	BLANK
0261	Sander	C2	42	3	1) EE to ME and operation is done with wood and sand paper. 2) Debris collected is seperated. 3) Final polished wood

**Table C.7: Sander Results (FB-II)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	-	-	56	-	BLANK
1378	Drilling Machine	J1	309	1	Screwing and positioning of solid is a function. Both outputand input are solid
8193	Band Saw	J1	187	3	Multiple solids in (Blade, wood). Air moves electric.

2879	-	-	166	-	BLANK
3631	Coffee Grinder	H2	58	3	Input side: No human action. Guiding solid + pneumatic input: coffee beans + Air
0580	Cloth Drier	D4	150	4	1) Input of EE, solid, gas. 2) Output of solid
1956	Unsure	-	161	1	Heat energy to separate solid
4258	Nail Gun	F3	129	3	Pn. E
8838	Nail Gun	F3	0	2	Solid and Pneumatic Energy
9311	-	L4	189	2	Guide Solid
9157	-	-	0	-	BLANK
8499	Vacuum Cleaner	F4	196	1	BLANK
1573	Vacuum cleaner	F4	150	2	Gas in. Solid in. Speperate solid, store solid. Gas out. Pnueamatic energy?
3622	-	-	0	-	BLANK
6251	Pencil Sharpener	J3	150	2	Description of solid flow
3904	-	-	0	-	BLANK
7731	Coffee Maker	H2	125	-	BLANK
0261	Hand Vacuum	B4	66	2	EE is converted to ME

**Table C.8: Sander Results (Pruned –II)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
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2458	Nail Gun	F3	73	3	Solids are separated. Nail separated from ?
1378	Coffee Maker	H2	283	1	The action of seperating solids
8193	Sharpener	J3	118	5	Solid/HE in, some solid out but other stopped. No Thermal energy involved.
2879	Hair Curler	L2	213	3	Electricity generates mechanical energy. Also much heat as input. (* User Thought HE was heat)
3631	Weed Whacker	E2	90	4	EE + HE on input side.
0580	-	-	0	-	BLANK
1956	Not Sure	Not Sure	107	1	The function model has too few details making it ambiguous.
4258	Sander	C2	145	2	Separate solid from solid. Pneumatic energy
8838	Jar Opener	L3	126	2	Separate solid from solid, but store only. Can opener or jar opener
9311	-	K2	239	1	Output Pn.E
9157	Jar Opener	L3	192	4	Seperating a soild (jar cap). Storing a solid (jar) Using Pn. E
8499	Juice Maker	H3	203	3	In juice maker juice is stored and part of it is disposed.
1573	Sander	C2	20	4	Solid in. Separate soild. Store part of solid using Pn. E.
3622	Coco Smasher	H2	227	2	1) Solid only when output. 2) Store solid
6251	Cotton Candy	L4	185	1	BLANK
3904	-	H4	145	3	EE - HS. ME - Pn.E Store

					solid
7731	Nailer	F3	190	3	Store solid
0261	Vacuum Cleaner	I1	112	1	EE to ME. Solid is collected and stored.

**Table C.9: Shopvac Vacuum Results (DR)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	Vacuum cleaner	B4	106	4	Solid + air mixture. Solid separated to debris. Solid + air is separated
1378	Vacuum Cleaner	F4	221	4	Input debris. Output debris . Indicates grinder action
8193	Sander	C2	211	1	Debris/air in, separated lots of human input. Con: Th. E Involved
2879	Vacuum Cleaner	F4	55	4	Uses hand. Uses Pn. Energy. Debris + air is input and separates as output. Works on electricity.
3631	Cleaner	F4	232	3	Debris and air. Hand: Vacuum action: Hand vacuum
0580	Shop Vacuum	I1	140	4	1) Input of air, HF, Hand, EE. 2) Use of rotational energy to convert ME to Pn.E
1956	Coffee Maker	H2	295	2	Debris, Hand, output air and debris
4258	Sander	C2	300		Separate debris from air
8838	Vacuum cleaner	I1	288	2	Separate gas and solid. Lots of human force. Again, which vacuum cleaner?

9311	Vacuum Cleaner	I1	315	1	Debris (input as well as output). Separating of solid from gas.
9157	Sander	C2	50	1	Air and debris as input giving debris as output. Using Hand to guide solid.
8499	Hand Vac	B4	135	3	<b>BLANK</b>
1573	Vacuum Cleaner	F4	116	4	Debris and air in. Separated outl. Difference between F4 and B4? Weight?
3622	Hand Vac	B4	90	4	1) Acoustic Energy output. 2) Weight output. 3) Air input and output. 4) EE. 5) Debris/air input, separate the two in output.
6251	Vacuum Cleaner	F4	36	4	The import of air and debris with an export of clean air indicated a vacuum. My confidence rating is 4 because there are two vacuum options.
3904	Hand Vac	B4	65	5	Solid gas mixture. EE to mechanical
7731	Hand Vac	B4	94	3	Solid debris plus air. Rotation energy. Acoustic energy (noise)
0261	Vacuum Cleaner	B4	86	4	1) Input is dust debris. 2) Waste is collected 3) Hot air and noise is sent out

**Table C.10: Shopvac Vacuum Results (Pruned-Free)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
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2458	Hand Vacuum	B4	64	4	Debris separated from air.
1378	Sander	C2	60	2	Debris as output
8193	Vacuum Cleaner	I1	64	5	Air/Debris comes in, separates, and leaves separately. Not handheld because no Human Energy signals.
2879	Vacuum Cleaner	F4	144	4	Works on electricity. Absorbs debris and air and leaves it back at the end. Absorbs solid parts and separates it from gas/air. Stores solid (Dust).
3631	Vacuum Cleaner	I1	48	5	Store solid. EE to Pn. E
0580	Vacuum Cleaner	I1	236	2	1) Convert EE to Pneumatic Energy
1956	Vacuum Cleaner	I1	71	4	Debris & gas. Store solid
4258	Hand Vacuum	B4	64	3	Store debris. Debris
8838	Vacuum Cleaner	I1	65	4	Debris and air mixture. Separate debris from air. Store Debris
9311	Vacuum Cleaner	F4	55	4	Input, output debris
9157	Vacuum Cleaner	F4	44	4	Using debris and air as input. Separating debris
8499	Vacuum Hand	B4	56	5	BLANK
1573	Vacuum Cleaner	F4	20	5	Debris + air in. Air out. Debris Store
3622	Cleaner	F4	37	5	1) Air input/output. 2) Separate gas and solid. 3) Debris output
6251	Shop Vac	I1	80	3	Separation of gas and debris



3904	hand Portable Vac	B4	31	4	EE - Pn. E. Debris - Output
7731	Hand Vacuum	B4	31	4	Debris and air input. Store solid(dust
0261	Grass Cutter	C4	77	2	Both air and debris (gases) enters at a time. Separate air and debris is got as o/p. Pn. E is used to the function

**Table C.11: Shopvac Vacuum Results (FB-II)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	Carpet Vacuum	F4	0	2	Solid plus gas. Solid is seperated. Pnematic energy is used.
1378	Sander	C2	344	1	Vague guess
8193	-	-	0	-	-
2879	-	-	0		-
3631	Vacuum Cleaner	F4	62	4	Soldi plus gas input. Separate solid from gas. EE to HE on input side.
0580	-	-	0	-	-
1956	Juicer	H3	116	1	Solid. Solid gas mixture
4258	Vacuum Cleaner	F4	164	2	Pneumatic Energy. Dunno if hand vac or full vac.
8838	Vacuum Cleaner	B4	147	4	Import Gas and solid mixture. Separate gas from solid.
9311	-	I4	226	1	Rotational Energy. Acoustics

9157	-	-	240	-	Blank
8499	Dryer	D4	211	4	Solid gas mixture is clothes and air, we export gas after the process is done. It give acoustic energy, gas is exported but after drying.
1573	Vacuum Cleaner	F4	35	5	Solid/gas in. Gas out. Solid stored. The. Acoustics created (by products)
3622	Cleaner	F4	110	4	1) Solid, gas mixture input. 2) Solid, gas separated. 3) Acoustic energy output. 4) EE
6251	Hand Vacuum	B4	95	1	Emphasis on human force
3904	Lawn Mower	C4	252	2	Solid gas mixture in. Solid and gas out
7731	Dryer	D4	108	4	Guide solid is gas. Thermal energy and process gas. Rotational Energy. Acoustic Energy
0261	vacuum Cleaner	F4	128	1	Solid-gas is similar to dust in room. HE is also expensed after vacuum cleaning. Noise comes. HE is used to guide cleaning.

**Table C.12: Shopvac Vacuum Results (Pruned –II)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	Vacuum Cleaner	I1	103	2	Theres way too many bacuum cleaners and function strucutres that are similar.
1378	Vacuum Cleaner	F4	33	1	Store solid. Input EE

8193	Popcorn Air Popper	J4	124	4	Heated air, solid/gas interaction. Could have been clothes dryer but air/solid mixture does not fit well there
2879	Vacuum Cleaner	F4	226	3	Take guiding gas( assuming it is air) Takes solid (dust) + gas(air) as input. Output is solid and gas separate
3631	-	H4	121	2	Not sure. Looking @ pictures.
0580	-	-	0	-	BLANK
1956	Vacuum Cleaner	I1	103	4	Separate solid from gas. Store solid. Input solid gas mixture
4258	Vacuum	F4	32	4	Store solid. Solid/Gas mixture
8838	Vacuum Cleaner	F4	50	4	Separate gas and solid. Guide gas. I know this is a vacuum cleaner, but which one. Isn't the purpose of function modeling to allow for multiple solutions of the same end goal?

9311	Vacuum Cleaner	I1	112	2	Solid/ gas. Pneumatic energy
9157	Solid Shooter	D3	106	4	EE converting to Pn. E. Solid + Gas separating as solid and gas
8499	Candy Mixture	L4	79	3	Input is electrical energy. Output is solid.
1573	Vacuum Cleaner	F4 or E4	25	4	Gas/solid mixture. Separate gas from solid. F4 or B4?
3622	Cleaner	F4	101	4	1) Solid gas mixture input. 2) Solid/gas separated output. 3) store solid
6251	Vacuum Cleaner	F4	25	2	Difficult to distinguish from shop vac.
3904	Vacuum Cleaner	B4 or F4	67	3	Store solid. EE - pneumatic
7731	Vacuum Cleaner	F4	90	4	Store solid (dust). Guide solid gas mix.
0261	Hand held dust cleaner	B4	175	1	EE is given as input. Solid is stored and gas sent out.

**Table C.13: Screwdriver Results (DR)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
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2458	Electric screwdriver	B1	84	4	ME is used to control. EE to ME is used to guide solid
1378	Screwdriver	B1	7	2	Output screw. Guide hand
8193	Electric Screwdriver	B1	39	5	"Screw", "hand"
2879	Nail Shooter	F3	63	3	Assuming screw as nails since screw is output. Mechanical work is output (nails are shot) Hand is used for direction
3631	Hand drill	H1	50	4	Screw human energy on input.
0580	Electric Screwdriver	B1	79	3	1) Input of hand & EE. 2) Output of screw and ME
1956	Screwdriver	B1	81	3	Screw. Output screw
4258	Drill	H1	107	2	Hand operated. Screw

8838	Electric Screwdriver	B1	64	4	Screw. Hand
9311	Nail Shooter	F3	39	4	Import solid. Input and output screw
9157	Electric Screw	B1	66	5	Using EE converting it into ME to guide a solid using screw
8499	-	-	0	-	BLANK
1573	Screwdriver	B1	25	4	Screw
3622	Drill	H1	57	4	1) Drill. 2) EE
6251	Screwdriver	B1	50	4	The use of the word "screw"
3904	Electric Screwdriver	B1	34	-	Direction, hadn, EE to ME
7731	Bread toaster	I2	137	3	Solid gудie. Use HS to CS
0261	Hand held screw driver	1	130	1	The output is to screw the object. The screw is first inserted by hand. EE to ME

**Table C.14: Screwdriver Results (Pruned-Free)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	Electric Screwdriver	B1	33	5	Screw, electric energy used to guide solid
1378	Screwdriver	B1	19	4	Input EE. Output screw and mechanical energy
8193	Electric Screwdriver	B1	48	5	"screw"
2879	Electric Screwdriver	B1	35	5	Uses electricity and screws as inputs. Given mechanical <i>energy</i> as output.
3631	Gun	E3	106	2	Guide Solid (bullet). Heat: mechanical.
0580	-	-	0	-	-
1956	Screwdriver	B1	79	4	Input screw. Output screw. Working material solid.
4258	Electric Screwdriver	B1	102	3	Screw
8838	Electric Screwdriver	B1	64	4	Screw. Guide Solid
9311	Nail Shooter	F3	57	1	Input/output screw
9157	Hand Drill	H1	132	3	EE converting to ME. Guidng a block using screw as input and getting ME and screw output

8499	Hole Driller	H1	30	5	Simple mechanism with a screw
1573	Screwdriver	B1	25	4	Screw
3622	Drill	H1	30	4	1) Screw output. 2) EE to ME
6251	Screwdriver	B1	68	4	Use of screw
3904	Screwdriver	B1	60	4	Screw, guide solid
7731	E. Screw drive	B1	27	4	Screw. Simple. Guide solid to screw.
0261	Nail Hitter	F3	38	2	The output is to screw. Nail is guided into the system

**Table C.15: Screwdriver Results (FB-II)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	Salad Thrower	D3	300	2	Solid is exported
1378	Jar Opener	L3	233	1	Conversion of EE to ME. Output is solid. Input is solid.
8193	Sewing Machine	G2	172	4	2 Different solids in. 1 is a signal source. (Hurts Decision because EE is exported!? No items do)



2879	-	-	0	-	BLANK
3631	Bread Toaster	I2	37	5	Solid @ input side. Convert solid to CS
0580	Nail Gun	F3	89	-	BLANK
1956	Band Saw	J1	141	2	Guide solid. Input is solid
4258	Salad Shooter	D3	71	1	?
8838	Salad Tosser	D3	306	2	No human energy. Only import, guide, export solid.
9311	-	-	0	-	BLANK
9157	-	-	331	-	BLANK
8499	Camera	C1	171	4	Has mechanical winding, camera film is imported and exported.
1573	Pencil Sharpener	J3	225	2	Take a solid and use it as a control signal. Solid in and out. EE out?
3622	Cooker	J4	177	3	1) EE to ME. 2) Solid in put/output
6251	Can Opener	J2	100	2	Indicating that the debice guides the solid.
3904	M/C Gun	E3	120	3	Guide solid, Import Solid

7731	S-Shooter	D3	178	3	Guide solid. Solid to C.S. Transfer ME to guide solid.
0261	Cotton Candy maker	L4	64	1	Both input and output is solid. EE is used to automate candy making.

**Table C.16: Screwdriver Results (Pruned-II)**

Student	Product Name	Product ID	Time Taken (sec)	Confidence	Comments
2458	Jar Opener	L3	70	3	ME is used to guide solid: Lid of the jar
1378	Toaster	I2	26	1	Input is heat/soild/EE. Output Solid
8193	Band Saw	J1	116	3	Solid in, solid out, ME out HE in.
2879	Nail Shooter	F3	160	1	Mechanical energy is Output. Solid(nail) is output
3631	CD Player	K3	50	3	Human Energy: CS: Button operated. EE to ME: rotate the disk(Solid)
0580	Salad Shooter	D3	77	3	1) Input of He and EE. 2) Guide solid. 3) Output of solid.
1956	Unsure	-	118	1	Too few functions

4258	Candy Machine	L4	56		None
8838	Nail Gun	F3	0	1	I honestly have not clue
9311	Lawn mower	C4	45	1	Guide solid
9157	Electric Screwdriver	B1	124	4	Guiding solid using electric energy as input
8499	Wood Cutter	F1	114	2	Simple mechanism
1573	Can Opener	L3	90	2	Mechanical energy out. Guiding a solid. No presence of heat(Th. E) but where is Rotational energy
3622	Cutter	F1	200	3	1) Human energy input. 2) Solid input, solid/ mechanical energy output
6251	Pencil Sharpener	J3	140	3	Export of solid indicated a cutting action
3904	Microwave	A2	176	2	Heat to mechanical
7731	Pencil Sharpener	J3	184	2	Guide solid. Very simple.
0261	Motor	I4	183	2	Electric energy is converted to mechanical energy. Control signal is

					given to aid feedback
--	--	--	--	--	--------------------------

## APPENDIX D: USER STUDY WORKSHEETS

The following pages are the user study worksheets participants used in identifying products based on each function structure representation.

Last 4 digits of your CUID

**A**  
**GREEN-1**

(1) Record START TIME below:

START TIME

HH:MM:SS

(2) Identify the product from the function structure shown below.

```
graph LR
    HE[HE] --> F1[Convert HE to CS]
    F1 -- CS --> F2[Convert EE to Th. E]
    EE[EE] --> F2
    F2 -- Solid --> S1[Store Solid]
    F2 -- Liquid --> S2[Store Liquid]
    S1 -- Solid --> F3[Mix Solid & Liquid]
    S2 -- Liquid --> F3
    F3 --> Out[Solid-Liquid Mixture]
    F3 -.-> F1
    F3 -.-> F2
```

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME

HH:MM:SS

**Figure D.1: Page 1 of Packet 1 (Rice Cooker-Pruned II)**

<div><div></div><div></div><div></div><div></div></div> <div>Last 4 digits of your CUID</div>				<div>A</div> <div>GREEN-1</div>
<div>(6)</div> <div>How confident are you in your decision? Please circle.</div>				
<div><div>1</div><div>2</div><div>3</div><div>4</div><div>5</div></div> <div><div>(Low/Not Sure)</div><div>(High/Extremely Confident)</div></div>				
<div>(7)</div> <div>What information in the model aided you in your decision?</div>				
<div>(8)</div> <div>Record END TIME below:</div>				
<div><div>END TIME</div><div>HH:MM:SS</div></div>				

**Figure D.2: Page 2 of Packet 1 (Rice Cooker – Pruned II)**

Last 4 digits of your CUID

**A**  
**GREEN-2**

(1) Record START TIME below:

START TIME

HH:MM:SS

(2) Identify the product from the function structure shown below.

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME

HH:MM:SS

**Figure D.3: Page 3 of Packet 1 (Sander – DR)**

Last 4 digits of your CUID

A

GREEN-2

(6)

How confident are you in your decision? Please circle.

1

2

3

4

5

(Low/Not Sure)

(High/Extremely Confident)

(7)

What information in the model aided you in your decision?

(8)

Record END TIME below:

END TIME

HH:MM:SS

**Figure D.4: Page 4 of Packet 1 (Sander –DR)**



Last 4 digits of your CUID

**A**  
**GREEN-3**

(1) Record START TIME below:

START TIME

HH:MM:SS

(2) Identify the product from the function structure shown below.

```

graph LR
    HE --> C1[Convert HE to CS]
    C1 -.->|On/Off| C2[Convert EE to ME]
    EE --> C2
    Direction -.-> C2
    C2 -- ME --> C3[Guide Solid]
    Screw --> C3
    C3 -- ME --> ME_out[ME]
    C3 --> Screw_out[Screw]
  
```

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME

HH:MM:SS

**Figure D.5: Page 5 of Packet 1 (Electric Screwdriver – Pruned Free)**



Last 4 digits of your CUID

**A**  
**GREEN-4**

(1) Record START TIME below:

START TIME

HH:MM:SS

(2) Identify the product from the function structure shown below.

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME

HH:MM:SS

**Figure D.7: Page 7 of Packet 1 (Shopvac Vacuum – FB-II)**



Last 4 digits of your CUID

**A**  
RED-1

(1) Record START TIME below:

START TIME

HH:MM:SS

(2) Identify the product from the function structure shown below.

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME

HH:MM:SS

**Figure D.9: Page 1 of Packet 2 (Rice Cooker – DR)**

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Last 4 digits of your CUID

A

RED-1

**(6)** How confident are you in your decision? Please circle.

1
2
3
4
5

(Low/Not Sure)
(High/Extremely Confident)

**(7)** What information in the model aided you in your decision?

**(8)** Record END TIME below:

END TIME

HH:MM:SS

**Figure D.10: Page 2 of Packet 2 (Rice Cooker – DR)**

Last 4 digits of your CUID

**A**  
**RED-2**

(1) Record START TIME below:

START TIME

HH:MM:SS

(2) Identify the product from the function structure shown below.

```

graph LR
    EE[EE] --> CEE[Convert EE to Pn.E]
    CEE --> TG[Th.E]
    CEE --> PG[Guide Gas]
    CEE --> PGSM[Guide Solid Gas Mixture]
    PG --> Air1[Air]
    PG --> TE[Th.E]
    PG --> Air2[Air]
    PGSM --> PnE1[Pn.E]
    PGSM --> DGA[Debris & Air]
    PGSM --> SG[Separate Solid from Gas]
    SG --> PnE2[Pn.E]
    SG --> Air3[Air]
    SG --> SS[Store Solid]
    SS --> D[Debris]
    SG --> PG
    SG --> PGSM
  
```

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME

HH:MM:SS

**Figure D.11: Page 3 of Packet 2 (Shopvac Vacuum – Pruned Free)**

Last 4 digits of your CUID

A  
RED-2

(6)

How confident are you in your decision? Please circle.

1

2

3

4

5

(Low/Not Sure)

(High/Extremely Confident)

(7)

What information in the model aided you in your decision?

(8)

Record END TIME below:

END TIME

HH:MM:SS

Figure D.12: Page 4 of Packet 2 (Shopvac Vacuum – Pruned Free)



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Last 4 digits of your CUID

A

RED-3

(1) Record START TIME below:

START TIME

HH:MM:SS

(2) Identify the product from the function structure shown below.

```

graph LR
    EE[EE] --> F1[Convert EE to ME]
    HE1[HE] --> F2[Convert HE to CS]
    CS[CS] --> F1
    F1 -- ME --> F3[Convert ME1 to ME2]
    F2 -- ME --> F4[Convert ME to P/L/E]
    F3 --> F5[Separate Solid]
    HE2[HE] --> F5
    Solid1[Solid] --> F5
    F5 -- Solid --> Solid2[Solid]
    F5 -- Solid --> F6[Store Solid]
    F4 -- P/L/E --> F6
    F6 -- Solid --> Solid3[Solid]
    F6 -- P/L/E --> PLE[P/L/E]
    
```

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME

HH:MM:SS

**Figure D.13: Page 5 of Packet 2 (Sander – Pruned II)**

<div><div></div><div></div><div></div><div></div></div> <div>Last 4 digits of your CUID</div>				<div>A</div> <div>RED-3</div>
<div>(6) How confident are you in your decision? Please circle.</div> <div><div>1</div><div>2</div><div>3</div><div>4</div><div>5</div></div> <div><div>(Low/Not Sure)</div><div>(High/Extremely Confident)</div></div>				
<div>(7) What information in the model aided you in your decision?</div>				
<div>(8) Record END TIME below:</div> <div><div>END TIME</div><div>HH:MM:SS</div></div>				

**Figure D.14: Page 6 of Packet 2 (Sander – Pruned II)**

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Last 4 digits of your CUID

A

RED-4

(1) Record START TIME below:

START TIME

HH:MM:SS

(2) Identify the product from the function structure shown below.

```

graph LR
    Solid1[Solid] --> ImportSolid1[Import Solid]
    ImportSolid1 -- Solid --> GuideSolid1[Guide Solid]
    GuideSolid1 -- Solid --> ExportSolid[Export Solid]
    ExportSolid -- Solid --> Solid2[Solid]
    GuideSolid1 -- Solid --> ConvertSolid[Convert Solid To CS]
    ConvertSolid -.- CS --> ActuateEE[Actuate EE]
    EE1[EE] --> StoreEE[Store EE]
    StoreEE -- EE --> SupplyEE[Supply EE]
    SupplyEE -- EE --> TransferEE[Transfer EE]
    TransferEE -- EE --> ActuateEE
    ActuateEE -- EE --> RegulateEE[Regulate EE]
    EE2[EE] --> ConvertEE[Convert EE To ME]
    ConvertEE -- ME --> ChangeME[Change ME]
    ChangeME -- ME --> TransferME[Transfer ME]
    TransferME -- ME --> GuideSolid2[Guide Solid]
    GuideSolid2 -- EE --> EE3[EE]
    GuideSolid2 -- Solid --> Solid3[Solid]
    Solid4[Solid] --> ImportSolid2[Import Solid]
    ImportSolid2 --> GuideSolid2
  
```

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME

HH:MM:SS

**Figure D.15: Page 7 of Packet 2 (Electric Screwdriver – FB II)**

Last 4 digits of your CUID				
<div>A RED-4</div>				
(6) How confident are you in your decision? Please circle.				
1	2	3	4	5
(Low/Not Sure)		(High/Extremely Confident)		
(7) What information in the model aided you in your decision?				
(8) Record END TIME below:				
END TIME		HH:MM:SS		

**Figure D.16: Page 8 of Packet 2 (Electric Screwdriver FB-II)**

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Last 4 digits of your CUID

A

ORANGE-1

(1) Record START TIME below:

START TIME

HH:MM:SS

(2) Identify the product from the function structure shown below.

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME

HH:MM:SS

**Figure D.17: Page 1 of Packet 3 (Shopvac Vacuum - Pruned II)**

<div><div></div><div></div><div></div><div></div></div> <div>Last 4 digits of your CUID</div>				<div>A</div> <div>ORANGE-1</div>
<div>(6)</div> <div>How confident are you in your decision? Please circle.</div> <div><div>1</div><div>2</div><div>3</div><div>4</div><div>5</div></div> <div><div>(Low/Not Sure)</div><div>(High/Extremely Confident)</div></div>				
<div>(7)</div> <div>What information in the model aided you in your decision?</div>				
<div>(8)</div> <div>Record END TIME below:</div> <div><div>END TIME</div><div>HH:MM:SS</div></div>				

**Figure D.18: Page 2 of Packet 3 (Shopvac Vacuum - Pruned II)**

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Last 4 digits of your CUID

**A**

**ORANGE-2**

(1) Record START TIME below:

START TIME
HH:MM:SS

(2) Identify the product from the function structure shown below.

```

graph LR
    EE_in[EE] --> ImportEE[Import EE]
    ImportEE --> TransferEE[Transfer EE]
    TransferEE --> AdjustEE[Adjust EE]
    AdjustEE --> RegulateEE[Regulate EE]
    RegulateEE --> ConvertEE[Convert EE to TH, E]
    ConvertEE --> TransferTHE[Transfer TH, E]
    TransferTHE --> ExportSolid[Export Solid]
    ExportSolid --> Solid_out[Solid]
    
    HE_in[HE] --> ImportHE[Import HE]
    ImportHE --> ConvertHE[Convert HE to CS]
    ConvertHE --> EE_in
    
    Solid_in1[Solid] --> ImportSolid1[Import Solid]
    ImportSolid1 --> PositionSolid[Position Solid]
    PositionSolid --> MixSolidLiquid[Mix Solid & Liquid]
    
    Solid_in2[Solid] --> ImportSolid2[Import Solid]
    ImportSolid2 --> StoreSolid[Store Solid]
    StoreSolid --> MixSolidLiquid
    
    Liquid_in[Liquid] --> ImportLiquid[Import Liquid]
    ImportLiquid --> StoreLiquid[Store Liquid]
    StoreLiquid --> MixSolidLiquid
    
    MixSolidLiquid --> ExportMixture[Export Mixture]
    ExportMixture --> Solid_out
    
    EE_in -.->|regulate| AdjustEE
    EE_in -.->|off| ConvertEE
    EE_in -.->|off| ExportSolid
  
```

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME
HH:MM:SS

**Figure D.19: Page 3 of Packet 3 (Rice Cooker – FB II)**





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Last 4 digits of your CUID

**A**

ORANGE-3

(1) Record START TIME below:

START TIME
HH:MM:SS

(2) Identify the product from the function structure shown below.

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME
HH:MM:SS

**Figure D.21: Page 5 of Packet 3 (Electric Screwdriver – DR)**

Last 4 digits of your CUID

A

ORANGE-3

(6)

How confident are you in your decision? Please circle.

1

2

3

4

5

{Low/Not Sure}

{High/Extremely Confident}

(7)

What information in the model aided you in your decision?

(8)


Record END TIME below:

END TIME

HH:MM:SS

**Figure D.22: Page 6 of Packet 3 (Electric Screwdriver – DR)**

Last 4 digits of your CUID

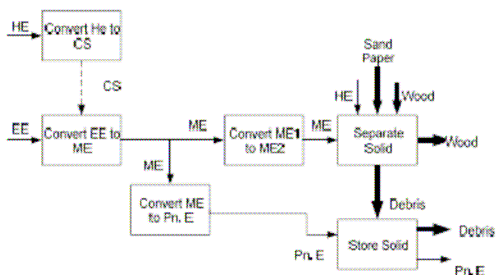


(1) Record START TIME below:

START TIME

HH:MM:SS

(2) Identify the product from the function structure shown below.



(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME

HH:MM:SS

**Figure D.23: Page 7 of Packet 3 (Sander – Pruned Free)**

<div><div></div><div></div><div></div><div></div></div> <div>Last 4 digits of your CUID</div>				<div>A</div> <div>ORANGE-4</div>
<div>(6) How confident are you in your decision? Please circle.</div> <div><div>1</div><div>2</div><div>3</div><div>4</div><div>5</div></div> <div><div>(Low/Not Sure)</div><div>(High/Extremely Confident)</div></div>				
<div>(7) What information in the model aided you in your decision?</div>				
<div>(8) Record END TIME below:</div> <div><div>END TIME</div><div>HH:MM:SS</div></div>				

**Figure D.24: Page 8 of Packet 3 (Sander – Pruned Free)**





Last 4 digits of your CUID

**A**  
BLUE-2

(1) Record START TIME below:

START TIME

HH:MM:SS

(2) Identify the product from the function structure shown below.

```

graph LR
    HE[HE] --> B1[Convert HE to CS]
    B1 -.-> CS[CS]
    CS -.-> B2[Convert EE to ME]
    EE[EE] --> B2
    CS -.-> B2
    B2 --> ME[ME]
    ME --> B3[Guide Solid]
    Solid[Solid] --> B3
    B3 --> ME_out[ME]
    B3 --> Solid_out[Solid]
  
```

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME

HH:MM:SS

**Figure D.27: Page 3 of Packet 4 (Electric Screwdriver – Pruned II)**





<div><div></div><div></div><div></div><div></div></div> <div>Last 4 digits of your CUID</div>				<div>A</div> <div>BLUE-3</div>
<div>(6)</div> <div>How confident are you in your decision? Please circle.</div>				
<div><div>1</div><div>2</div><div>3</div><div>4</div><div>5</div></div> <div><div>(Low/Not Sure)</div><div>(High/Extremely Confident)</div></div>				
<div>(7)</div> <div>What information in the model aided you in your decision?</div>				
<div>(8)</div> <div>Record END TIME below:</div>				
<div><div>END TIME</div><div>HH:MM:SS</div></div>				

**Figure D.29: Page 5 of Packet 4 (Electric Screwdriver – Pruned II)**

Last 4 digits of your CUID

A

BLUE-3

(1) Record START TIME below:

HH:MM:SS

(2) Identify the product from the function structure shown below.

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

HH:MM:SS

**Figure D.30: Page 6 of Packet 4 (Sander – FB II)**

Last 4 digits of your CUID

**A**  
**BLUE-4**

(1) Record START TIME below:

START TIME

HH:MM:SS

(2) Identify the product from the function structure shown below.

```

graph TD
    HE --> F1[Convert HE to CS]
    F1 -.-> F2[Convert EE to Tlx E]
    EE --> F2
    On --> F2
    Off --> F2
    Bowl --> F3[Store Solid]
    Rice --> F3
    F3 --> F4[Mix Solid & Liquid]
    Water --> F5[Store Liquid]
    F5 --> F4
    F4 --> BowlOut[Bowl]
    F4 --> RiceOut[Rice]
  
```

(3) Product Name: \_\_\_\_\_

(4) Product ID: \_\_\_\_\_

(5) Record END TIME below:

END TIME

HH:MM:SS

**Figure D.31: Page 7 of Packet 4 (Rice Cooker – Pruned Free)**

<div><div></div><div></div><div></div><div></div></div> <div>Last 4 digits of your CUID</div>				<div>A</div> <div>BLUE-4</div>
<div>(6) How confident are you in your decision? Please circle.</div> <div><div>1</div><div>2</div><div>3</div><div>4</div><div>5</div></div> <div><div>(Low/Not Sure)</div><div>(High/Extremely Confident)</div></div>				
<div>(7) What information in the model aided you in your decision?</div>				
<div>(8) Record END TIME below:</div> <div><div>END TIME</div><div>HH:MM:SS</div></div>				

**Figure D.32: Page 8 of Packet 4 (Rice Cooker – Pruned Free)**

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